Visualisation of the Lip Motion of Brass Instrument Players, and Investigations of an Artificial Mouth as a Tool for Comparative Studies of Instruments

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A thesis submitted in fulfilment of the requirements
for the degree of Doctor of Philosophy
to the
University *of* Edinburgh
2007

Abstract

When playing a brass instrument the lips of the player fulfil a similar role to the cane reeds of wood-wind instruments. The nature of the motion of this lip-reed determines the flow of air through the lips, between the player's mouth and the instrument. It is a complicated feedback system in which the motion of the lips controls the air flow, which itself affects the behaviour of the lips. In recent years several designs of artificial mouth have been developed; these model the human lips using latex rubber tubes filled with water. These artificial mouths are increasingly used in experiments rather than enlisting the services of a musician as they have many advantages including greater accessibility and the stability of the embouchure. In this thesis factors affecting the reproducibility of the embouchure of one such artificial mouth are investigated with reference to the measured resonances of the lips. Using these results, procedures and practical design improvements are suggested. Two examples of comparative studies of historic instruments are presented.

In order to provide detailed information on the behaviour of the lips of brass players high speed digital photography is used to image the self-oscillating lip-reed. Variation in the lip opening, over a wide range of notes and different players, is investigated, providing experimental evidence to aid the process of refining physical models of the behaviour of the brass player's lips. Particular attention is paid to the relationship between the area and height of the lip opening. Results suggest that during extremely loud playing the lip motion is qualitatively similar to that in quieter notes and therefore is not the origin of the dramatic increase in the levels of the high harmonics of the radiated sound. Investigation of the behaviour at the start of a note has shown evidence relating the lip motion to the transient in the mouthpiece pressure waveform. Comparison is made between the behaviour of the artificial lips and that of the lips of musicians providing evidence of the suitability of the use of the artificial mouth as a model for real brass players. Results show that although differences exist, particularly when looking at behaviour over a wide range of dynamic levels, the general features of behaviour are reproduced by the artificial mouth.

Declaration

I do hereby declare that this thesis was composed by myself and that the work described within is my own, except where explicitly stated otherwise.

Seona Bromage

April 2007

Acknowledgements

Firstly I would like to thank Murray Campbell for all the help support and guidance I have received. I would also like to thank Clive Greated who along with Murray introduced me to the field of musical acoustics ten years ago. Without their enthusiasm for the subject I probably would not have even started this work.

I would like to acknowledge the assistance provided by those with whom I have collaborated. Thanks to Joël Gilbert for his invaluable input on much of this work and for tolerating my lack of ability to speak French. Thank you to Arnold Myers for many useful suggestions and for providing the historic instruments. Thanks to John Chick for assistance with the transient and brassy measurements. I would like to acknowledge the assistance provided by Alistair Braden with the BIAS measurements, Sandra Carral and Felicien Vallet for the discussions and help with the spectral centroid results, and Michael Newton for providing the input response of the horn. Special thanks to Catherine Archbold for her help with some of the filming. To all those who volunteered their lips for investigation (Murray, Joël, AlistairJ, Tim, Sunil, Mike, Arnold, AlistairB, John, Anne) - I could not have done it without you.

Extra special thanks to Orlando Richards for all his help and support over the last ten years and for introducing me to his rubber lips. Thanks to Steve Tonge for being lovely and very helpful and to Alan Woolley, Calum Gray, Rob MacDonald and all the other acoustics people past and present, especially Sam Stevenson and Mike Newton - the lips are in your hands. Cheers to Darren Hendrie for all the disk quota and entertainment.

Without my husband David this would either have been finished ages ago or not at all. Thank you for everything including lots of Matlab support, making my dinner and for all the lovely love.

I would like to thank my sister Kathy her for all her patience and for being so wonderful. Finally I would like to thank my mum and dad for making me in the first place and and for cultivating my love of Edinburgh.

Financial support was provided by EPSRC.

Nomenclature

Musical notes and equivalent frequencies

Below are given approximate frequencies for some commonly referred to notes of the equal-tempered chromatic scale based on $\mathrm{A}_4 = 440\mathrm{Hz}$ ("Middle C" is C_4).

$\mathrm{B}\flat_1$	58.3 Hz
$\mathrm{B}\flat_2$	116.5 Hz
F_3	174.6 Hz
D_4	293.7 Hz
F_4	349.2 Hz

Musical dynamics

p	*piano*	"softly"
mf	*mezzo-forte*	"moderately-loud"
f	*forte*	"loudly" or "strong"
ff	*fortissimo*	"very loudly"

Lip parameters

m_{lip}	mass of lip
ω_{lip}	natural resonant (angular) frequency of lip
Q_{lip}	quality factor of lip resonance
F	driving force on lip (also used to denote some general function)
h	lip separation
h_0	time averaged lip separation
$h(\omega)$	oscillating component of lip opening
$\Delta P(\omega)$	oscillating pressure difference across the lips
S	area of lip opening
q	exponent in the area-height relationship

General symbols

z	specific acoustic impedance
Z	acoustic impedance
ω	angular frequency
p	acoustic pressure
P	pressure
u	acoustic particle velocity
S	cross sectional area
U	acoustic volume flow
ν	frequency
n	harmonic number
l	effective length

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Context and Motivation

Wind instruments are classified into brass or woodwind families not by the material from which they are constructed but by the method of excitation. For woodwinds this is the cane reed, which can be either a single strip of cane as in the clarinet or a pair of canes as in the oboe, bagpipe chanter etc. In brass instruments the source of oscillation is the player's lips themselves; these can be referred to as a *lip reed* and many characteristics of their behaviour can be examined in direct comparison with the cane-reed of the woodwind instruments. The nature of the motion of this lip-reed determines the flow of air through the lips, between the player's mouth and the instrument. It is a complicated feedback system in which the motion of the lips controls the air flow, which itself affects the behaviour of the lips. Over the last sixty years results from a small number of key visualisation studies have been used to provide information on the behaviour of the oscillating lips of brass players. These previous studies have generally used stroboscopic filming and are usually limited to a single player.

In recent years several designs of artificial mouths have been developed; these model the human lips using latex rubber tubes filled with water. When investigating the behaviour of the brass players lips artificial models of lips are increasingly used as these provide a more controllable and easily accessible subject for investigation. Few people can be persuaded to allow you to attach microphones and other probes inside their mouths, even if it were physically possible. It is often necessary to repeat a single note for several minutes or even hours and this is easily possible with an artificial mouth. When conducting comparative instrument studies the use of the artificial mouth allows a far greater control over the embouchure and hence reliably avoiding the variations inherent in human playing.

Investigation into the behaviour of the lip reed is part of the goal of developing a better understanding of the physical processes which result in sound production from brass instruments. More accurate physical models of the lips can be used in combination with existing models of the instrument to give better synthesis results. This can in itself be interesting and musically useful. Accurate models incorporating results from non-invasive physical measurements of fragile or delicate historical instruments may, in future, provide authentic reproductions of the sound of instruments that can no longer be played. Similar models could also be used to test new instrument designs making use of optimisation techniques.

1.2 Aims

The aims of this study are to:

- Investigate factors affecting the reproducibility and control of the embouchure of the artificial mouth.
- Image the self-oscillating lip-reed using a high speed camera; to investigate variations in the opening between the lips over a range of notes and using

different players.

- Make a comparison of the behaviour of the artificial lips and that of the lips of musicians in order to provide evidence of the suitability of the use of the artificial mouth as a model for real brass players.
- Explore the use of the artificial mouth as a tool for use in investigation and comparison of historic instruments.

1.3 Content

Chapter 2 introduces the basics of brass instrument acoustics relevant to this study. This includes a discussion of the behaviour of the lips of the player; the air column in the instrument; and the airflow which couples them together.

Chapter 3 details an investigation of the stability of the embouchure of the artificial mouth. Factors affecting the reproducibility are investigated with reference to the measured resonances of the lips. Using these results procedures are developed and suggestions for future improvements in the design of the artificial mouth are made.

Chapter 4 presents work using high speed digital photography to image the self-oscillating lip-reed. The primary focus is on the study of variations in the opening between the lips over a range of notes and using different players. Comparison is made between the behaviour of the artificial lips and that of the lips of musicians providing evidence of the suitability of the use of the artificial mouth as a model for real brass players. Particular attention is paid to the relationship between the area and height of the lip opening. Behaviour during extremely loud playing is also studied.

Chapter 5 is an extension of the work in chapter 4 focusing on the lip motion during the starting transient of a note. The lip motion is related to the mouthpiece pressure waveform.

Chapter 6 presents two examples of comparative studies of historic instruments exploring the role of the artificial mouth as a tool for use in such studies.

In chapter 7 a summary of the conclusions of this thesis are presented and suggestions for future work are then given.

Appendix A gives some additional results.

Appendix B contains a series of lips images corresponding to the data given in figure 4.32 (left).

Appendix C gives a list of the films available on the accompanying CD.

Chapter 2

Brass instrument acoustics

Many standard texts on musical acoustics give a thorough description of various aspects of the theory of brass instrument acoustics; see for example [9, 14, 22, 44, 53]. The following is a review of the theory of brass instrument acoustics relevant to this study.

2.1 Overview

When describing the acoustics of brass instruments, or any wind instrument, it is helpful to consider the system to be made from three parts: the mechanical oscillator that is the reed or lips; the acoustic resonator that is the air column in the instrument; and the airflow which couples them together. The three parts of the system combine in a feedback loop as shown in figure 2.1. In brass instruments the nature of the motion of the player's lips determines the flow of air between the player's mouth and the instrument. It is a complicated feedback system in which the motion of the lips controls the air flow, which itself affects the behaviour of the lips. Because of the highly non-linear actions involved even a seemingly insignificant change in any part of this system of player and instrument can result

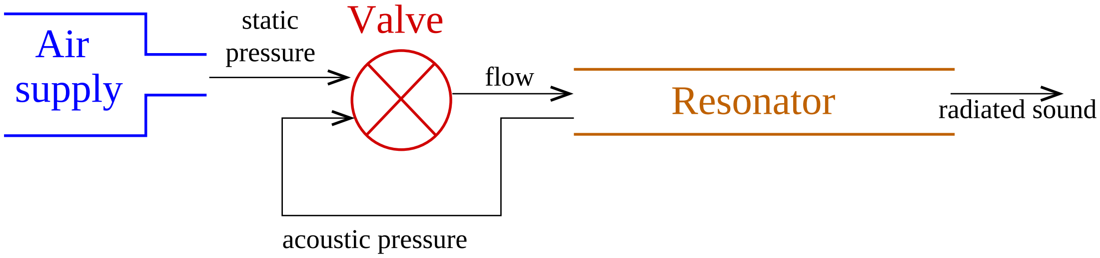


Figure 2.1: A wind instrument can be thought of in three parts: a *resonator*; a pressure controlled *valve* which modulates the *air flow*. In a brass instrument the air column in the instrument is the resonator and the lip-reed, formed by the lips of the player pressed against the rim of the mouthpiece, is the valve which controls the air flow.

in a significantly different output sound.

2.2 The air column in the instrument

2.2.1 Impedance

The specific acoustic impedance, z, as a function of angular frequency, ω, is defined as the ratio of acoustic pressure $p(\omega)$ to the acoustic particle velocity $u(\omega)$.

$$z(\omega) = \frac{p(\omega)}{u(\omega)}. \tag{2.1}$$

The acoustic impedance Z is defined as the ratio of acoustic pressure $p(\omega)$ at a surface of cross sectional area S to the acoustic volume flow $U(\omega)$ through that surface, where $U(\omega) = u(\omega)S$.

$$Z(\omega) = \frac{p(\omega)}{U(\omega)}. \tag{2.2}$$

The input impedance is defined as the acoustic impedance Z at the entrance to the instrument. It is a function of angular frequency and describes the strength of the pressure fluctuation for a given amount of alternating flow through the lips.

The input impedance can be measured experimentally and the resulting input impedance curve is a useful description of the particular characteristics of the air column of the instrument.

2.2.2 The instrument as a simple resonator

The air flow entering the instrument is modulated by the lips allowing a periodic input of regions of high and low pressure. This pressure wave, a plane wave as a first approximation, travels along the air column and is partially reflected at any point where there is a change in the acoustic impedance. Such partial reflections occur at, for example, a change in the cross section of the bore, the location of tone holes and also the end of the instrument where some sound is radiated. If the air column has a resonance close to the frequency of the pressure wave then a standing wave develops.

The trombone, trumpet and (to a lesser extent) the horn are predominantly cylindrical in nature at least for a significant proportion of their length. The lip reed, like other reeds acts as a closed end and therefore the air column has a pressure antinode at the lips and a pressure node close to the open end. An ideal cylinder closed at one end has a harmonic series of resonances at frequencies, ν_n, given by:

$$\nu_n = \frac{2n-1}{4l}c, \tag{2.3}$$

where n is the harmonic number $(1, 2, 3...)$, l is the effective length of the cylinder, and c is the speed of sound in air. The effective length, l is not simply the physical length of the tube. The anti-node is located a distance approximately $D/3$ from the end of the tube, where D is the diameter of the tube. So the effective length l is in fact $D/3$ longer than the physical length of the instrument.

The air column inside the bore of the instrument has a series of acoustic resonances, each of which can be modelled approximately as an acoustic oscillator, the physics of which is well understood and described in many standard texts, see for example [44].

2.2.3 The shape of real brass instruments

A real instrument is not just a length of cylindrical tubing, but has a mouthpiece at the one end, a flared bell at the other and narrowed sections at the connections to the mouthpiece. It may also have valves, a slide or a number of tone holes (as does the ophicleide described in section 6.2). All these contribute to determining the actual resonances of the instrument and mean that the playing behaviour of a real brass instrument is far from that of the simple closed cylinder described above. It is vital for the playability of the instrument that these features are designed correctly so as to achieve the most beneficial set of resonances[14]; this is discussed in section 2.4.3. The series of resonances of a simple cylinder are given by equation 2.3 and playing an instrument with these resonances would produce only the odd-numbered members of a harmonic series. However the combined effect of the bell and the mouthpiece gives a series of resonances which are close to a complete harmonic series [22] except for the fundamental.

The effect of the mouthpiece

The mouthpiece is a vital part of the the instrument body as it provides a rigid structure against which the player's lips can be pressed. The mouthpiece and the players lips enclose a volume of air which acts as a simple Helmholtz resonator and therefore has its own resonance which is determined by the volume of air enclosed and the area of the opening in the throat of the mouthpiece. The main acoustical effect of the mouthpiece is to strengthen some of the impedance peaks around the mouthpiece resonant frequency in the middle of the instrument's playing range.

There is also a more subtle effect on the frequencies of the peaks [22] as the added volume increases the effective length of the instrument and so reduces the frequencies of the higher modes.

The effect of the bell

A good approximation to the shape of a real instrument is given by a section of cylindrical tubing joined to a flaring section. The flaring section or Bessel horn can be described in terms of the relationship between a the bore radius and x the distance along the bore from the mouth of the horn as defined by equation 2.4

$$a = b(x + x_0)^{-\gamma}, \tag{2.4}$$

where γ defines the rate of flare (0.7 being realistic value for trumpets and trombones[104] and x_0 and b are chosen to give the desired radii at each of the ends of the horn. Benade[14] calculated the resonance frequencies of this model to be approximately given by ν_n in equation 2.5:

$$\nu_n \approx \frac{c}{4(l + x_0)} \Big((2n - 1) + \beta(\xi(\xi + 1))^{0.5}\Big) \tag{2.5}$$

In general terms the bell has the effect of shortening the effective length of the air column at low frequencies where the wavelength is much longer than the radius of curvature of the bell [22].

Slides and valves

The inclusion of valves or a slide in the instrument both serve to introduce extra sections of tubing to increase the length of the air column and so allow a different harmonic series of notes. The addition of extra tube length necessitates a degree of compromise in design of the bell and mouthpiece in order to optimise the harmonicity of the modes [23].

The effect of tone holes

The effective length of an instrument is altered by the presence of holes in the bore. As you open a hole in the bore of the instrument this allows the air column at that point to mix with the air outside. The pressure node moves from (close to) the end of the instrument to a position further up, shortening the effective length [22]. The amount by which the presence of a hole alters the speaking length is determined by the diameter of the hole. If the hole diameter is comparable to the tube radius then it acts as an open end and the tube is effectively cut off at this point. If the hole is very small (as in a speaker hole) then it will have very little effect. Otherwise the tone hole will cause the speaking length to be partially reduced [22]; this effect is frequency dependent[14]. The tone holes exist to allow notes to be played which do not coincide with one of the natural resonances of the full air column. As well as changing the pitch of the note they also have an effect on the timbre [14]. The open hole acts as a high pass filter, the cutoff frequency being dependent on the tone hole proportions, small holes giving a low cutoff frequency and large holes have a high cutoff frequency. For this reason the presence of large toneholes in an instrument often results in timbral variations with different fingering patterns.

2.3 The lips - mechanical oscillator

The physics of the reeds of wood-wind instruments, such as the clarinet or oboe, has long been well described [54, 14, 44] with the reed itself being modelled as a single mass on a spring. However the brass player's lips are seemingly more difficult to describe and model as they are a complicated non-rigid structure of mus-

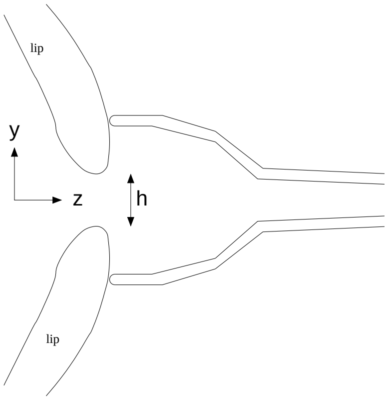


Figure 2.2: The lips exhibit motion both vertically in the plane of the lip opening (y-direction) and also horizontally perpendicular to this plane (z-direction).

cles and other tissue for which a full description would require a series of lumped oscillators; though various simplifications can be made [32]. Studies[64] have shown that the lips exhibit motion both vertically in the plane of the lip opening (y-direction) and also horizontally perpendicular to this plane (z-direction). The horizontal motion of the lips causes air to be displaced by this motion of the lips. It is assumed however that the horizontal motion does not significantly affect the flow through the lip channel, and that the vertical component of motion is controlling the flow[32].

2.3.1 One mass model

Elliot and Bowsher [37] first gave a simplified description of the lip-reed as a single mass on a spring with one degree of freedom. This *one mass model* is discussed in detail by various texts, for example [32]. When considering low amplitude behaviour, as when playing just above the threshold of oscillation, the model acts as a driven simple harmonic oscillator, the driving force is provided by the fluid forces acting on the lip.

Each lip can be described as a simple mass on a damped spring, the dynamics of which is given by the equation for a damped simple harmonic oscillator:

$$\frac{\partial^2 y}{\partial^2 t} + \frac{\omega_{lip}}{Q_{lip}}\frac{\partial y}{\partial t} + \omega_{lip}^2 y = \frac{F_y}{m_{lip}}, \tag{2.6}$$

where m_{lip} is the mass of one lip; ω_{lip} and Q_{lip} are the natural resonant (angular) frequency of the lip and the quality factor of that lip resonance. F is the driving force on the lip. By assuming that the two lips behave symmetrically and are separated by a rectangular opening of height $h(t) = 2y(t)$:

$$\frac{\partial^2 h}{\partial^2 t} + \frac{\omega_{lip}}{Q_{lip}}\frac{\partial h}{\partial t} + \omega_{lip}^2 h = \frac{F_y}{m_{ef}}, \tag{2.7}$$

The driving force F can be split approximately into the horizontal force, F_z, due to the pressure difference across the lips (between the over-pressure in the mouth and the oscillating mouthpiece pressure) and secondly the vertical force, F_y, due to the pressure in the lip channel.

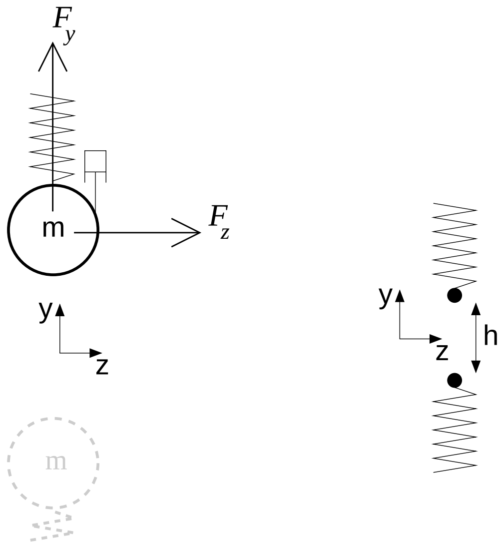


Figure 2.3: A simple lip model.

2.3.2 Pressure controlled valve

The vibrating lips of the brass player allow a steady flow from the lungs to be converted into an oscillating flow which couples with the instrument to produce a self-sustained oscillation. The oscillation of the lip reed is both controlled by and is controlling the air flow into the instrument. In order for the oscillation to be sustained it must occur in such a way as to add energy to the system in order to balance that lost to friction and radiation etc.

The lip reed, like other reeds acts as a closed end, and is therefore a pressure anti-node of the instrument where the pressure fluctuates above and below a mean value. The particular way in which the reed responds to these pressure fluctuations depends on its geometry and leads to the classification described below.

Reed Types

Most musical reeds can be described as exhibiting behaviour either classed as *striking inwards* or *striking outwards* depending on how the reed responds to a slow increase in blowing pressure. Striking inwards behaviour is characterised by a slow increase in blowing pressure causing the reed to close, as has been shown to be the case with the reeds of woodwind instruments such as the clarinet [6]. The action of the reed is defined as striking outwards if a slow increase in blowing pressure causes the reed to open. Reed behaviour was first categorised in this way by Helmholtz [54] and the description expanded by Fletcher [41, 44].

In order to supply energy to the standing wave and therefore allow self-sustained oscillation the reed must allow greatest flow into the instrument when the mouthpiece pressure is high and reduce the flow when the mouthpiece pressure is low, ie the pressure and flow velocity at the mouthpiece are in phase and the standing wave is strengthened. However as the lip-reed acts as a driven harmonic oscillator, there is in general a phase lag in the response of the lips to the driving pressure. If an inward striking reed is driven well below the frequency of its resonance then the lip opening and driving acoustic pressure in the mouthpiece are in phase. As the playing frequency increases to the reed resonance then the opening lags more behind the pressure signal until when driven at resonance the movement of the lips lags 90 degrees behind the pressure signal[46].

The criteria for self-sustained oscillation dictate the phase relationships, given in equation 2.8, between $h(\omega)$ the oscillating component of lip opening and $\Delta P(\omega)$ the oscillating pressure difference across the lips; assuming a constant supply pressure. For inward striking behaviour the phase difference $\angle C(\omega) = +\pi/2$ and for outward striking $\angle C(\omega) = -\pi/2$.

$$\angle C(\omega) = \angle h(\omega) - \angle \Delta P(\omega) \tag{2.8}$$

Inward striking behaviour only sustains standing waves at a frequency less than the reed resonance and also less than the acoustic resonance. Outward striking behaviour only sustains standing waves when playing at a higher frequency than both the reed resonance and the acoustic resonance. The fact that brass players are able to ‘lip’ notes both above and below the instrument resonance suggests that neither reed type alone can be responsible for all playing behaviour and that both regimes are in operation. Recent studies[32][83][74] have indeed shown that the lips of a brass player seem to act as both inward and outward striking reeds, so allowing the player to produce notes above, below and at the resonant frequencies of the instrument. In order to do this the player makes adjustments to their lip muscles so that the lip resonant characteristics fulfil the criteria for sustained oscillation as described above[22].

2.4 The air flow - nonlinearity

The pressure control valve determines the flow into and out of the instrument. The lip motion itself can be modelled as a simple mechanical oscillator (see section 2.3.1) and the air column in the instrument can be described as a linear resonator. However the relationship between the pressure difference across the lip-valve and the flow through it is highly non-linear. The volume flow rate $U(t)$ of the air passing through the valve into the instrument is some non-linear function F of the pressure difference:

$$U(t) = F(\Delta P), \tag{2.9}$$

where the pressure difference ΔP across the reed is given by

$$\Delta P = P_m - P_i(t), \tag{2.10}$$

and where P_m is the pressure in the player's mouth, and $P_i(t)$ is the pressure inside the mouthpiece. The volume flow rate (or volume velocity) is the product of the particle velocity $u(t)$ and the area of the opening $S(t)$:

$$U(t) = S(t)u(t), \tag{2.11}$$

The large cross sectional area of the mouth compared to the lip channel means that the velocity in the mouth can be neglected and the particle velocity $u(t)$ in the lip channel is uniform [32]. By assuming quasi-stationary, frictionless and incompressible flow the Bernoulli equation can be used to determine the relationship between this particle velocity $u(t)$ in the lip channel and the pressure drop along the lip channel:

$$\Delta P = \frac{\rho({v_2}^2 - {v_1}^2)}{2} = \frac{\rho u^2}{2}, \tag{2.12}$$

Combining equations 2.11 and 2.12 gives:

$$U(t) = S(t)\sqrt{\frac{2\Delta P}{\rho}}, \tag{2.13}$$

The coupling of this non-linear valve to the resonator is the origin of the complicated relationship between the sound level of the note played and it's spectral content or 'timbre'.

2.4.1 Harmonic generation

Early measurements carried out by Martin[64] on the cornet showed almost sinusoidal lip motion and although studies of lip vibrations in the trombone by Copley and Strong[30] have shown that lips produce a more asymmetric area function in loud playing, this alone is not sufficient to account for the high frequency components of the brass sound. This view was developed by the work of Backus and Hundley[11] and Elliot and Bowsher[37] who have proposed a simple explanation for the generation of harmonics in brass instrument playing. As described in section 2.4 the behaviour of the flow control valve that is the lip opening is highly non-linear. The flow is determined not just by the lip opening but by the combination of the input impedance of the instrument and the time-varying impedance presented by the lips. When playing loudly and for low pitch notes the lip opening is, at its maximum, far greater than the cross sectional area of the throat of the mouthpiece (that is the narrowest part of the instrument's bore). If we consider the case of playing purely at the resonance, i.e. the player is not 'lipping the note' then we can consider the lip impedance to be purely resistive [22]. Elliott and Bowsher state that for a fully turbulent flow the resistance of the opening (rectangular slit of length l and height x) takes the form given in equation 2.14 [37].

$$R = \left(\frac{\rho}{2}\right)\left(\frac{U}{l^2x^2}\right) \tag{2.14}$$

For large amplitude lip openings the average resistance of the opening is low allowing the air to flow easily through with only a small pressure drop. When the lips are nearly closed the resistance is high and therefore the flow through the small opening requires a large pressure drop[37]. This means that during a portion of the cycle the pressure inside and outside the lips is approximately equal and the mouthpiece pressure is therefore effectively clipped; only when the lips are almost closed do they take over control of the waveform. This behaviour produces a non-sinusoidal mouthpiece pressure waveform of the form given in figure 2.4.

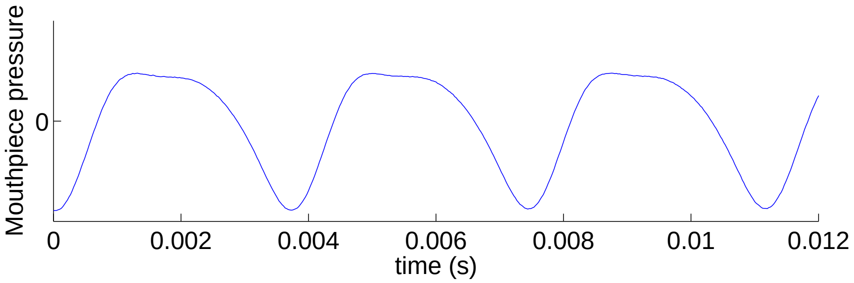


Figure 2.4: Mouthpiece pressure waveform showing ‘clipping’ due to non-linearity in the flow control valve that is the lip reed.

2.4.2 The brassy sound

The volume flow through the lip opening is determined by the area of the opening and the pressure difference across the lip-reed valve as defined in equation 2.9. This nonlinear relationship (described in section 2.4) is the origin of the non-sinusoidal waveforms of the pressure and flow measured in the mouthpiece [11, 37, 42]. The harmonic content of the sound at quiet and moderate playing levels is due to this primary nonlinearity of the lip-reed. Hirschberg *et al*[55] have shown that for high amplitude pressure oscillations generated in the mouthpiece, the leading edge of the pressure wave steepens as the wave progresses along the tube. If the amplitude of the pressure wave is large and the rise abrupt enough then the pressure rise may become near instantaneous for instruments whose air column is sufficiently long. This non-linear progression of the wavefront along the bore of the instrument results in a transfer of energy from low to high harmonics [42] and is generally accepted to be the origin of this ‘brassy’ sound [21].

2.4.3 Co-operative regimes of oscillation

The player sets their embouchure to enable the lips to vibrate at a particular frequency. This vibration modulates the flow into the instrument. In order for the oscillation to be sustained the frequency must be close to a resonance of the air column and fulfil the criteria set out in section 2.3.2.

If the behaviour of the air flow was simply linear then it would be sufficient to have a set of resonances for the notes you wish to play. The lip vibration and hence pressure fluctuation would generate a standing wave at the resonance. Although the air column can be described as a linear acoustic oscillator, the non-linear nature of the flow control valve complicates the system. It is not enough to only consider the fundamental frequency of oscillation as the resonator is coupled to the non-linear flow valve as described above.

If for example the player chooses to play F_3 at around 174 Hz then they would set the lips to oscillate, approximately sinusoidally, at about this frequency. The non-linear nature for the lip-valve produces fluctuations in the flow which are not sinusoidal, but contain harmonics of the fundamental. The fluctuations excite the air-column resonance close to 174Hz but also the upper harmonic components of the flow. If the air column also has resonances at these frequencies then the standing wave is further supported by this. If the air column has no other resonances harmonically related to the fundamental then energy is lost and the note is difficult to sustain [14]. It is for this reason that it is desirable to have harmonically related resonances.

2.5 Modelling the Brass player's lips

Cullen[32] details a system of three equations describing the playing behaviour of a brass instrument, adapted from a model presented by Elliott and Bowsher[37]. The three equations are:

- the resonant behaviour of the lips
- an impedance description of the air column in the instrument
- the non-linear flow equation

The resonant behaviour of the lips in the simplest description can be represented by the one mass model (see section 2.3.1) which describes the periodic variation of the lip separation $h(t)$. The air flow into the instrument is modulated by this oscillating valve that is the lips of the player. The acoustic volume flow controlled by the valve depends not only on the pressure difference across the lips but also on the area of the opening between the lips. It is therefore useful to describe the open area $S(t)$ as a function of the lip separation or opening height $h(t)$.

The simplest form of this function is derived from an assumption that the relationship is linear, the lip aperture can be described as a rectangle of constant width and time varying height; $S(t) \propto h(t)$. This assumption of constant width has been used in many models, for example [3, 37, 87]. An alternative form would be to assume width also varies with height, giving the quadratic relationship

$S(t) \propto h(t)^2$. This form of the relationship has been used by Msallam [67]. This area-height relationship is discussed further in section 4.4.

Chapter 3

Reproducibility and control of the artificial mouth

3.1 Introduction

Artificial mouths, based on the modelling of lips with latex tubes, have been extensively used in studies of brass instruments. The artificial mouth used in this study is shown in figure 3.1. One of the frequently stated [82, 50, 78] reasons is the ability to repeatedly play without many of the variations inherent in human playing. Any study of how an instrument plays is affected by the method used to produce the initial vibration. It is important to have a controllable playing mechanism that is as reproducible as possible.

Chapter 2 introduced the idea of using a system of 3 equations which together describe the playing behaviour of a brass instrument. The three equations are an impedance description of the acoustic behaviour of the air column; the non-linear flow equation and the resonant behaviour of the lips which in the simplest description is represented by the one mass model (see section 2.3.1). Both the

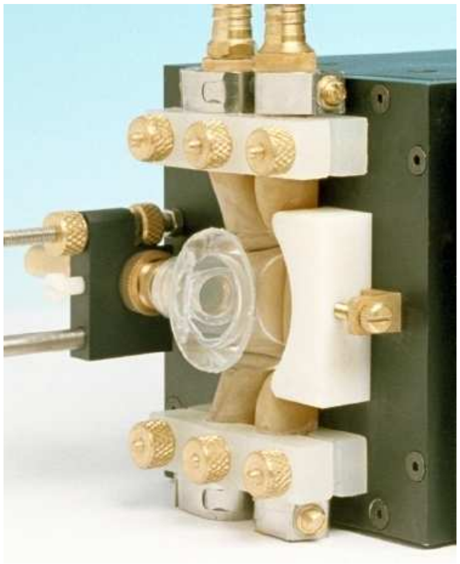


Figure 3.1: Artificial mouth used in experiments

second and third of these, the flow and the lip resonances, are determined by the player. A quantitative description of the lip resonances is therefore a useful tool for defining the playing embouchure.

When wanting to make accurate comparisons between instruments, for example in spectral or listening studies, it is important to eliminate the effect of the player and have a controllable playing mechanism that is as reproducible as possible. Any statement of similarity or variation between the sound obtained from different instruments relies on the reproducibility and control of the playing embouchure (the static configuration of the lips).

The mechanical resonance behaviour of the lips of an artificial mouth is related to characteristic parameters of the embouchure. These parameters include the rest position and internal pressure of the lips, and the extent to which the lips are squeezed by the pressure of the mouthpiece. In this chapter measurements of the mechanical response of the lips and the spectrum of the sound (measured in the mouthpiece shank) are studied for a range of different embouchure settings with the various parameters which determine the embouchure being set, changed and reset. Comparisons of results give some measure of the reproducibility of the system.

3.1.1 The lip response

As previously mentioned it is often sufficient to use a simple one mass model of the lips to reproduce many playing characteristics; however the true resonant behaviour of the lips is much more complicated. Previous studies[32][83][74] have shown that the lips of a brass player seem to act as both inward and outward striking reeds, so allowing the player to produce notes above, below and at the resonant frequencies of the instrument, and at least two degrees of freedom are needed to model this behaviour. Richards[82]has shown with experiments that a four degree of freedom model would be necessary to fully represent the main features of the lip motion.

By examining the magnitude and phase of the response of the lips to an applied acoustic pressure it is possible to identify resonant peaks that correspond to inward and outward striking modes of vibration. The criteria for self-sustained oscillation dictate the phase relationships, given in equation 3.1, between $h(\omega)$ the oscillating component of lip opening and $\Delta P(\omega)$ the oscillating pressure difference across the lips.

$$\angle C(\omega) = \angle h(\omega) - \angle \Delta P(\omega) \tag{3.1}$$

where P_m is the pressure in the player's mouth, and $P_i(t)$ is the pressure inside the mouthpiece and pressure difference ΔP across the reed is given by

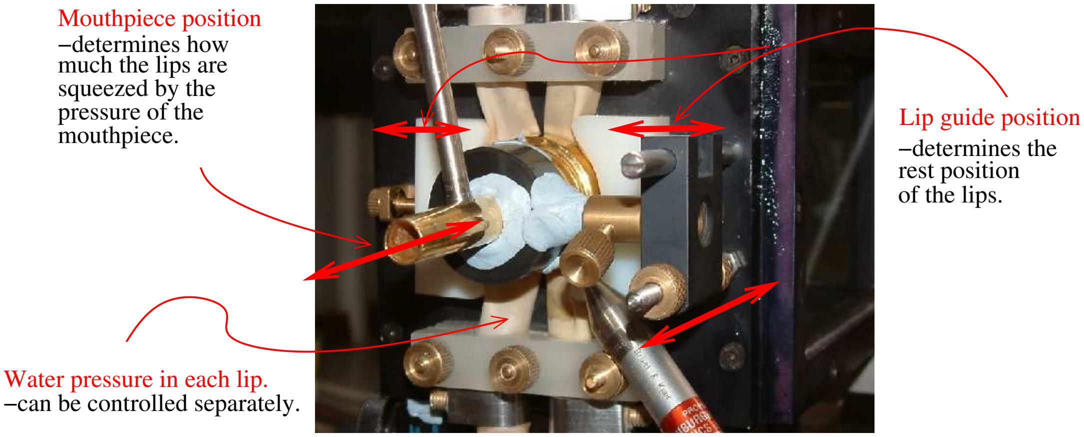
$$\Delta P = P_m - P_i(t). \tag{3.2}$$

For inward striking behaviour the phase difference $\angle C(\omega) = +\pi/2$ and for outward striking $\angle C(\omega) = -\pi/2$.

3.2 Design of the artificial mouth

There exist several designs of artificial mouth for playing brass instruments. The design used in this study (see figures 3.3 and 3.2) is that detailed by Richards[82]. It differs from designs used in earlier studies mainly in that the lips are mounted externally. This makes the mouth compatible with a wide variety of mouthpieces and enables easy adjustment of the embouchure. The parameters which can be adjusted are the rest position of the lips as determined by the position of the two lip guides (shown in figure 3.2), the internal water pressure of the lips, and the extent to which the lips are squeezed by the pressure of the mouthpiece, determined by the position of the mouthpiece relative to the mouth.

3.2.1 Characteristic parameters of the embouchure



Mouthpiece position
–determines how much the lips are squeezed by the pressure of the mouthpiece.

Lip guide position
–determines the rest position of the lips.

Water pressure in each lip.
–can be controlled separately.

Figure 3.2: Close up of artificial lips, showing lip guides and mouthpiece attachment.

- The internal pressure of the lips is supplied by a head of water which can be easily adjusted and measured.
- The rest position of the lips is controlled by adjusting the position of the lip guides using the thumb screws on which they are located. Their position is

quantified by the use of callipers and by reference to a fixed point on the wall of the mouth cavity.

- The extent to which the lips are squeezed by the pressure of the mouthpiece is adjusted by moving the mouthpiece holder along the mounting rails.

3.3 Experimental method

3.3.1 Setup

The overall setup is shown in figure 3.4. This is based on that used by Richards [82] and similar to that used by Cullen [32] and Neal [72]. The static overpressure in the mouth cavity was provided by an Air Control Industries Ltd 8MS11 0.25kW pump and measured using a Digitron p200UL manometer with a tube situated in a small hole in the mouth cavity wall. The flow from the pump to the mouth was controlled using a valve which allowed fine adjustments to be made so enabling the mouth overpressure to be set to the desired level. The amplitude of lip oscillation was measured by illuminating the lip opening and recording the

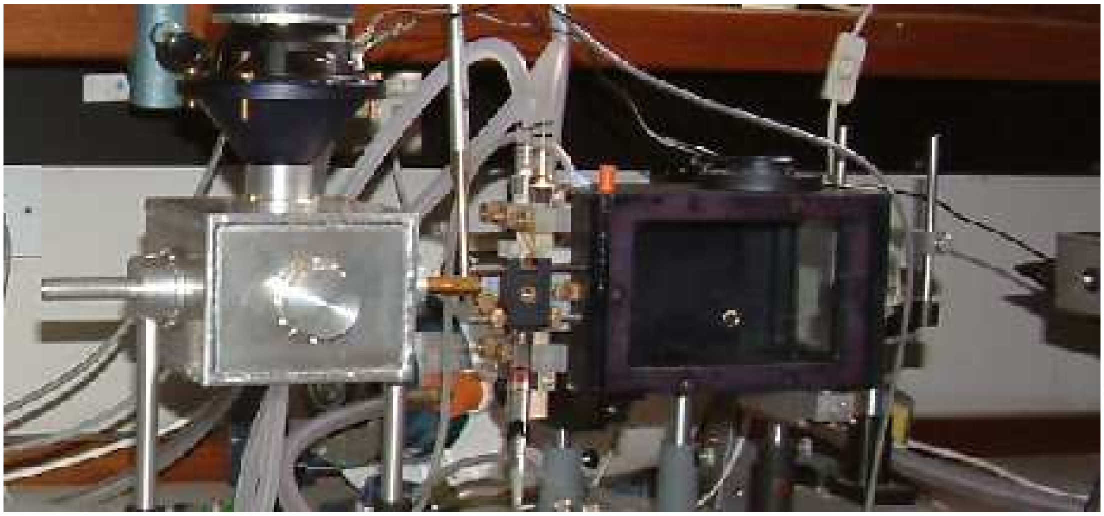


Figure 3.3: Experimental apparatus.

transmitted light on the far side, this being proportional to the height of the lip opening[32]. A small laser was used as the light source, the beam from which was expanded to illuminate the full height of the central portion of the lip opening visible through the mouthpiece shank. On the far side of the mouth cavity the light was focused on to a type IPL10530DAL Hybrid Detector photo-diode which had a linear response in the range of interest. The mouth and other apparatus were mounted on an optical rail to allow alignment of the various items as shown in figure 3.4

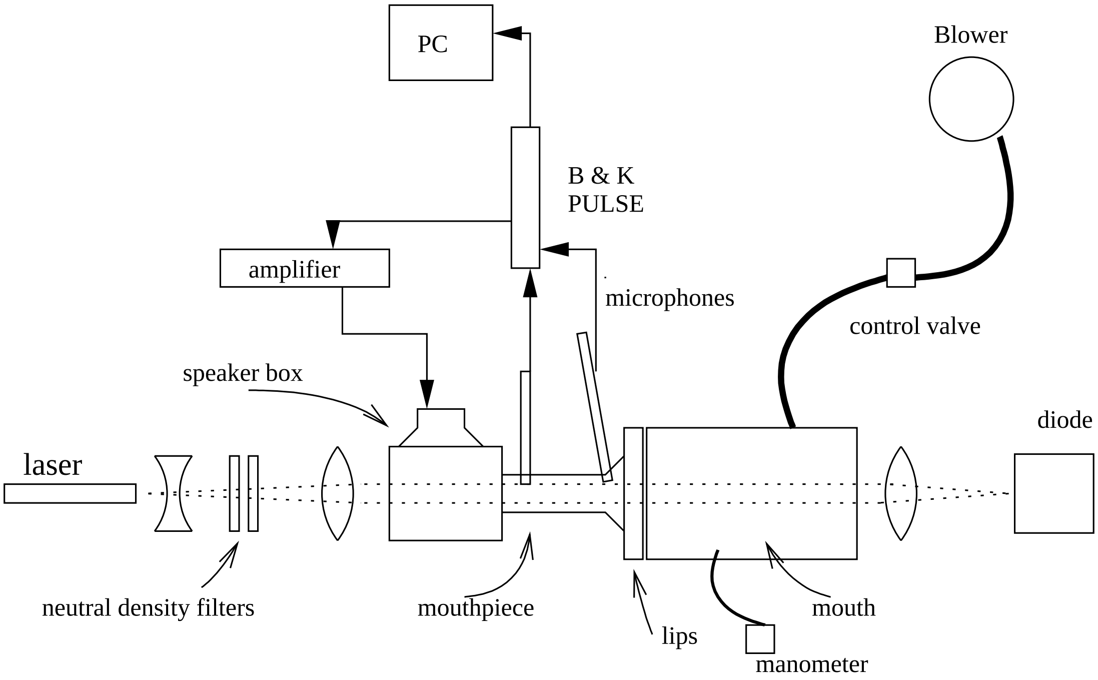


Figure 3.4: Experimental setup.

PULSE

The Brüel and Kjær PULSE system acts as an amplifier for the microphones, and provides real time data acquisition and processing capabilities. Data was collected from both the photo-diode and both microphones using the PULSE system.

3.3.2 Speaker mounting

In order to investigate the response of the lips to an applied acoustic pressure it is necessary to provide an appropriate coupling of the speaker to the system. During normal playing conditions the oscillating pressure which drives the lips is provided by the air column of the instrument downstream of the lips. A 'speaker box' was designed to allow a loudspeaker to be coupled to the mouthpiece in order to provide the acoustic pressure. The box was designed to have a sufficient cavity volume (13cm by 13cm by 10cm) so as not to have a strong resonance in the same frequency range as the lip resonances. Impedance measurements with the BIAS system[1] confirm the presence of a resonance at 570/580 Hz which is above the frequency range of the lip resonances measured. The box is mounted on the optical rail and has easily interchangeable attachment points for the mouthpiece.

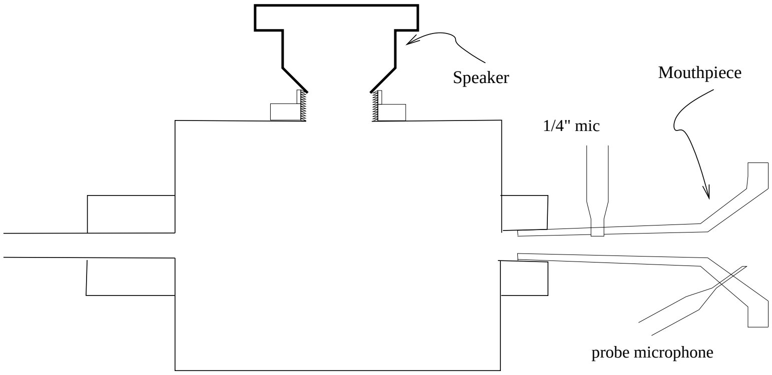


Figure 3.5: Speaker box and mouthpiece.

It is the pressure difference across the lips which provides the driving force so it is not necessary to drive from the downstream side and it is sometimes inconvenient to do so, for example when using an historical mouthpiece which can not be drilled to allow the insertion of the probe microphone. For this reason the mouth is designed to allow a speaker to be mounted on to the body of the mouth itself in order to apply the driving acoustic pressure from the upstream side; this can be then monitored using a microphone in the mouth cavity. Both methods are equivalent and simply require careful attention to the definition of the phase difference between the driving pressure and the resulting lip motion as a phase shift of π is introduced when shifting between downstream and upstream. The pressure difference is defined in equation 3.2 to be $P_m - P_i(t)$. The pressure in the player's mouth P_m is assumed to be constant, and therefore the pressure difference is simply $-P_i(t)$: that is, the pressure inside the mouthpiece phase shifted by π. If driving from the upstream side then the pressure on the mouthpiece side is assumed to be constant and the pressure difference is simply the mouth pressure P_m.

3.3.3 Measurement procedure

The following procedure was observed before each measurement set. The pressure in the mouth cavity was increased by opening the flow valve. This static overpressure in the mouth, once above the threshold of oscillation, caused the lips to oscillate. Adjustments were made to the various control parameters (lip-guide position, internal lip pressure, mouthpiece position) until a stable tone of the desired frequency was obtained. The sound in the mouthpiece shank was monitored using a Brüel and Kjær $\frac{1}{4}''$ microphone and the PULSE system as this allowed the playing frequency to be measured in real time. The $\frac{1}{4}''$ microphone was used as it was able to measure the high pressure levels present during playing without saturation. The mouth pressure was then reduced until the lips ceased to oscillate and allowed to rest for a moment. The mouth pressure was then increased again to ensure that the threshold of oscillation occurred at the same (within measurement accuracy) level of mouth overpressure and the same playing frequency and therefore that the embouchure was suitably robust. The lips were then allowed to sound for several minutes to ensure stability before recording a short portion of the sound. The flow valve was then closed reducing the mouth overpressure to zero before beginning the measurement of the lip response. It should be remarked that the parameters chosen in this study come from a relatively restricted set which have been found to give robust and stable playing behaviour.

Obtaining the lip response

To obtain the lip response the lips were excited from the downstream side by an acoustic pressure provided by the speaker mounted on a box as described in section 3.3.2. The signal used was a chirp over the frequency range 30Hz - 750Hz[82]. The driving pressure was measured in the mouthpiece with a Brüel and Kjær Type 4192 $\frac{1}{2}''$ microphone with short (31mm long) 2mm diameter probe. The calibration curve for this probe is given in figure 3.6; this was applied to the measurements in the post-processing in Matlab. The amplitude of the lip opening was measured using a photo-diode as described above. Data from the probe microphone and the photo-diode were collected using the Brüel and Kjær PULSE system. The system was configured to perform real-time FFTs on these signals and to calculate the deconvolution in order to give the magnitude and phase of the response of the lips to the applied acoustic pressure.

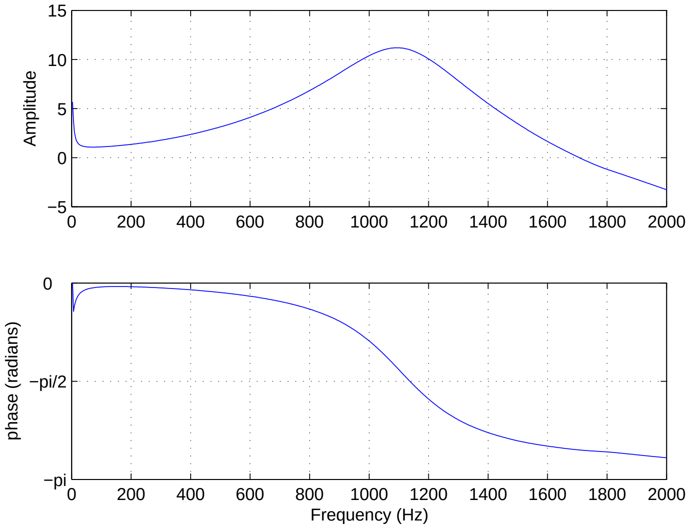


Figure 3.6: Calibration data for the short probe.

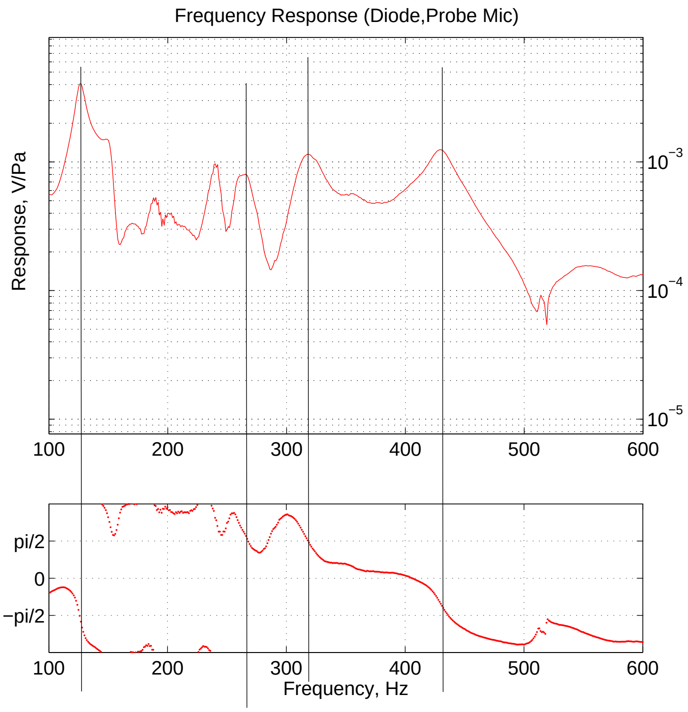


Figure 3.7: An example response curve; vertical lines indicate resonances.

Figure 3.7 gives an example lip response curve. As described in section 3.1.1 it is possible by examining the magnitude and phase of the response of the lips to the applied acoustic pressure to identify resonant peaks that correspond to inward and outward striking modes of vibration. For inward striking behaviour the phase difference $\angle C(\omega) = +\pi/2$ and for outward striking $\angle C(\omega) = -\pi/2$. Figure 3.7 shows several peaks corresponding to inward and outward striking modes of vibration; these are identified with vertical lines.

A program developed by Cullen[32] was used to fit curves to each of the resonances in the mechanical response. The program compares the response data to a theoretical resonance curve given by equation 3.3 [32]

$$A(f) = \frac{A_0}{\sqrt{1 + \frac{4Q_0^2(f-f_0)^2}{f_0^2}}} \tag{3.3}$$

which has a maximum value A_0 at frequency f_0 and quality factor Q_0. The program calculates the square of the difference between the theoretical curve and the measured data and then uses an iterative process to find the values of A_0, f_0 and Q_0 which minimise the squared difference. The program then outputs the frequency f_0, quality factor Q_0 and maximum valueA_0 for each of the fitted resonances. Figure 3.8 shows an example of the results of the curve fitting process.

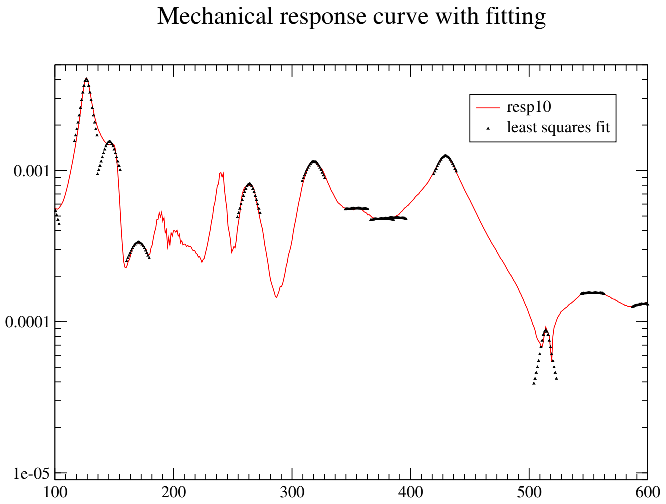


Figure 3.8: An example of fitted curves for determination of the frequency and quality factors of resonances

3.4 Measurements of repeatability and reproducibility

The characteristic parameters which determine the embouchure were set, changed and reset and measurements made of the mechanical response of the lips. Comparisons of the mechanical resonance behaviour of the lips after resetting the embouchure give some measure of the reproducibility of the system. Variations are related to the spectrum of the sound recorded in the mouthpiece shank (produced from a fixed mouth overpressure) to allow identification of the significance of these variations.

3.4.1 Unavoidable variations - repeatability

The initial question to answer is that of the stability of the system over time with no other alterations. To this end measurements were taken of the response of the lips repeatedly at approximately 5 minute intervals with no alteration between. The frequency of the note played was 204 Hz. Figure 3.9 shows five such repeated measurements of the mechanical response taken one after the other. There are small variations in the magnitudes of the resonance peaks; for example, the peak at 216 Hz varies from 6.5 to 9.9 mV/Pa. Frequencies were constant within experimental accuracy (1Hz resolution) and quality factors varied by around 10%. These variations are most likely due to the measurement procedure, rather than

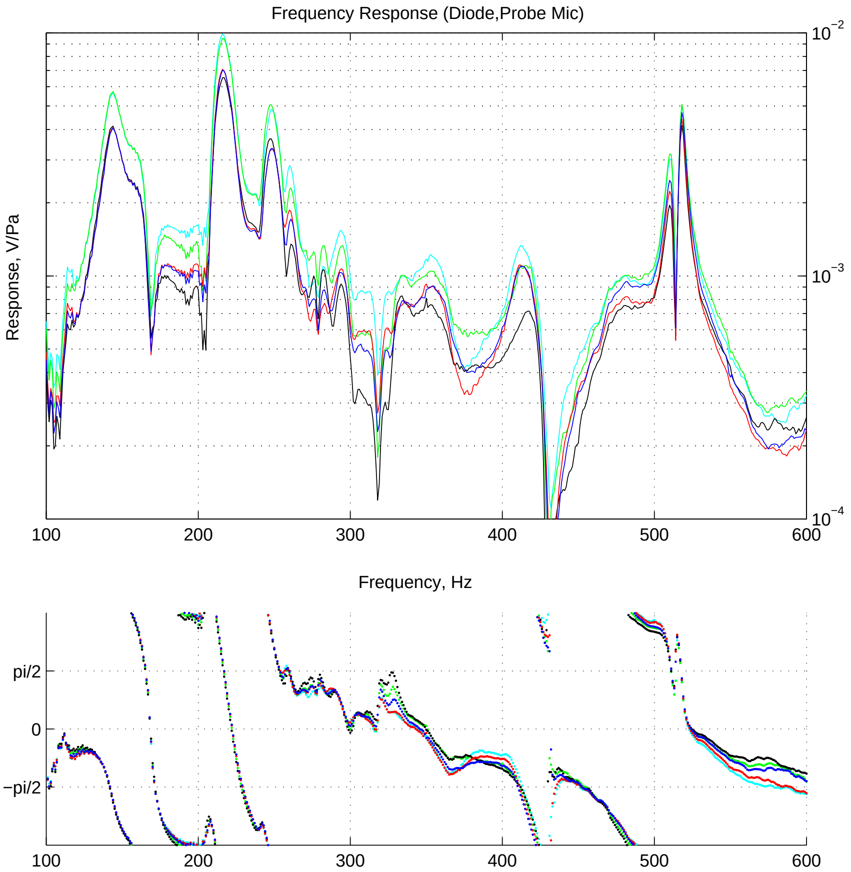


Figure 3.9: Five responses taken immediately one after the other.

actual changes in the embouchure. Fluctuations in the output from the laser have been observed and it is likely that these fluctuations could account for these small changes in the magnitudes of the resonance peaks.

Similar variations are observed when the pressure in the mouth cavity was increased above the threshold of oscillation and the lips left to oscillate for several minutes between each mechanical response measurement. Figure 3.10 shows five such measurements.

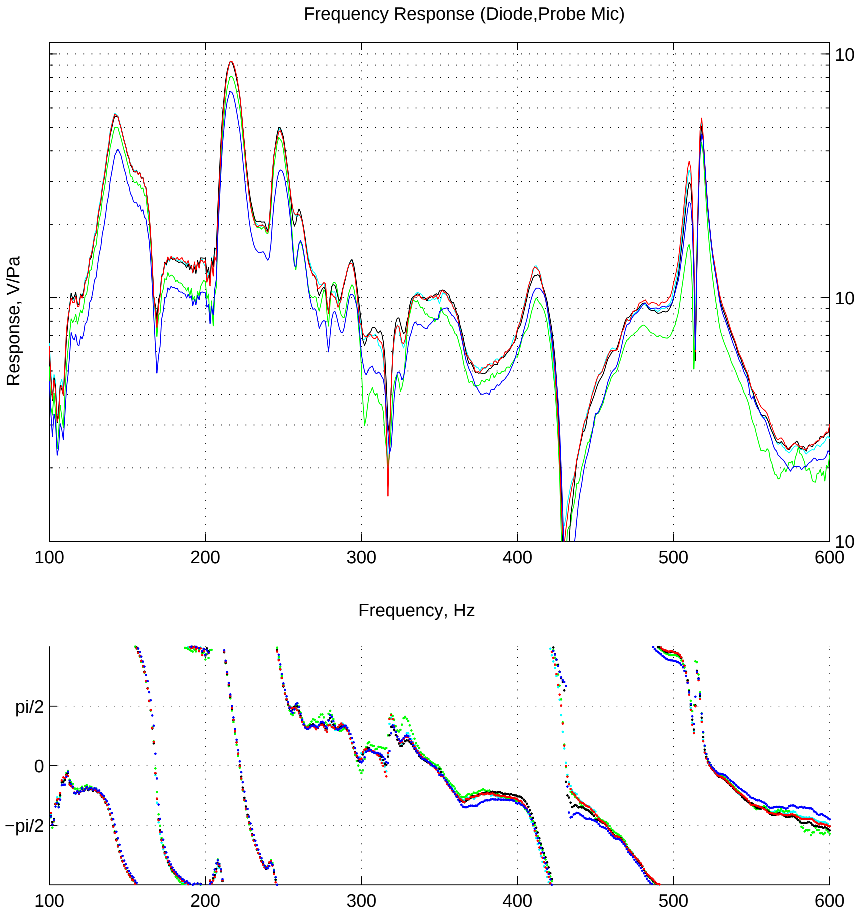


Figure 3.10: Five repeated responses, playing between.

Figure 3.11 again shows 5 such repeated measurements of the mechanical response, playing between measurements, but for a different initial embouchure. The frequency of the note played was 305 Hz. Two of the resonance peaks are marked and values obtained from the curve fitting are given in Table 3.1. The spectrum was produced of the sound in the mouthpiece shank for each of the five measurements. Comparison of the spectra shows that the levels of each of the first seven harmonic peaks vary by less than 4dB from one measurement to another. The levels of each of the other peaks detectable above the noise level vary by less than 8dB over the five repeated measurements. The overall sound level was calculated (using the root mean squared pressure signal) for each recording and this varied by less than 0.5dB from one measurement to another. The playing frequency was constant within the 1Hz resolution of the measurements.

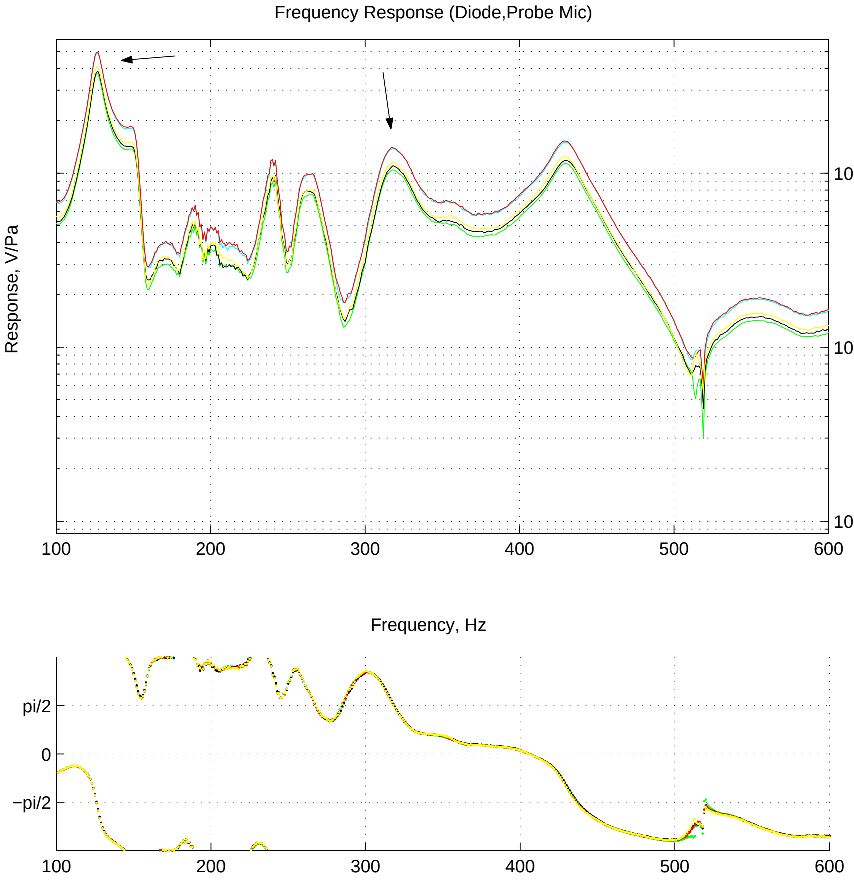


Figure 3.11: Five repeated responses, playing between (embouchure changed from figure 3.10).

Dataset colour	Frequency Hz	Response mV/Pa	Quality factor
black	127.0	3.9	15.5
green	126.5	3.7	15.0
cyan	127.0	4.8	15.0
red	126.5	4.9	15.0
yellow	126.5	4.0	15.0
black	318.5	1.1	15.5
green	318.5	1.0	14.0
cyan	318.5	1.4	14.5
red	318.0	1.4	16.0
yellow	318.5	1.1	14.5

Table 3.1: Values of frequency, amplitude and quality factors obtained by curve fitting to the resonances in the five responses curves shown in figure 3.11.

3.4.2 Resetting the embouchure control parameters

It has been found in practice that in order to make an effective change in the static position of the lips the mouthpiece must first be removed and then replaced to avoid the lips sticking to the mouthpiece surface. When simply altering and resetting the level of the internal lip pressure similar small variations are observed as described in the previous section. More significant variations are observed when the mouthpiece is moved and then replaced against the lips. Figure 3.12 shows five response curves obtained after this repeated resetting of the mouthpiece position. The same initial embouchure was used as in the measurements shown in figure 3.11 and Table 3.2 gives values for the same two marked resonance peaks. In contrast to the previous sets of measurements, here the overall sound level measured in the mouthpiece shank varied by 11.3 dB, and the playing frequency varied between 297Hz and 305Hz. The nature of a resonance peak, not just its frequency, is important in determining the output sound obtained. Focusing on the dominant resonance at approximately 320Hz it appears that variations in the quality factors of the resonance seem to correlate well with the pressure levels produced when playing. With the black and cyan curves (Q factors 34 and 23.5)

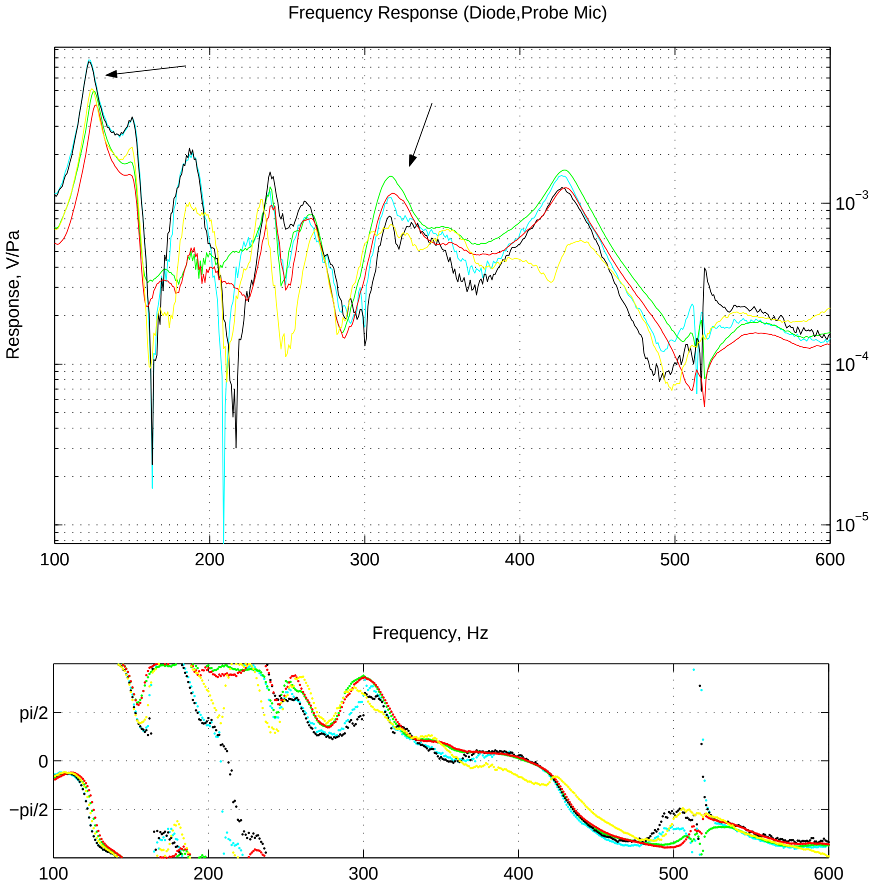


Figure 3.12: Five responses; mouthpiece position reset between measurements.

Dataset colour	Frequency Hz	Response mV/Pa	Quality factor
red	126.5	4.0	15.0
green	125.5	5.0	16.0
cyan	123.0	7.9	16.5
black	122.0	7.5	16.0
yellow	124.5	5.2	16.5
red	318.5	1.1	14.5
green	316.5	1.5	17.0
cyan	316.0	1.1	23.5
black	315.5	.83	34.0
yellow	316.0	.72	—

Table 3.2: Values of frequency, amplitude and quality factors obtained by curve fitting to the resonances in the five responses curves shown in figure 3.12.

the sound was much louder (+4.4dB and +4.6dB) than with the red and green curves (Q factors 14.5 and 17). With the yellow curve it was much quieter (a reduction of 6.7dB) and no curve could be matched to the resonance as it was so poorly defined. The standard deviation of the quality factors of the dominant resonance was 8.7; for the results given in Table 3.1 the standard deviation of the quality factors of the dominant resonance was only 0.8.

3.4.3 Reconnecting mouthpiece and instrument

When performing comparative studies of instruments it is often possible to use a single mouthpiece and swap between the instruments, connecting them in turn to the shank of the same mouthpiece. Figure 3.13 shows variations in the mechanical response curves obtained by moving and replacing the speaker box while the mouthpiece remains fixed in place in order to measure the effect on the embouchure of this type of procedure. The embouchure used was the same as that used to produce the results shown in figure 3.10. The process of connecting the mouthpiece shank to the instrument (speaker box) appears to be another possible source of significant embouchure variation with playing frequencies ranging between 205Hz and 209Hz. The standard deviation of the quality factors of the dominant resonance peak was 3.0 which is more than the unavoidable variations but less than the variations caused by resetting the embouchure control parameters.

3.4.4 Lip position

When the mouthpiece is in place the lips can still be ‘prodded’ into a wide range of positions. Figure 3.14 shows examples of different responses obtained in this way; playing frequencies ranged from 232Hz to 451Hz.

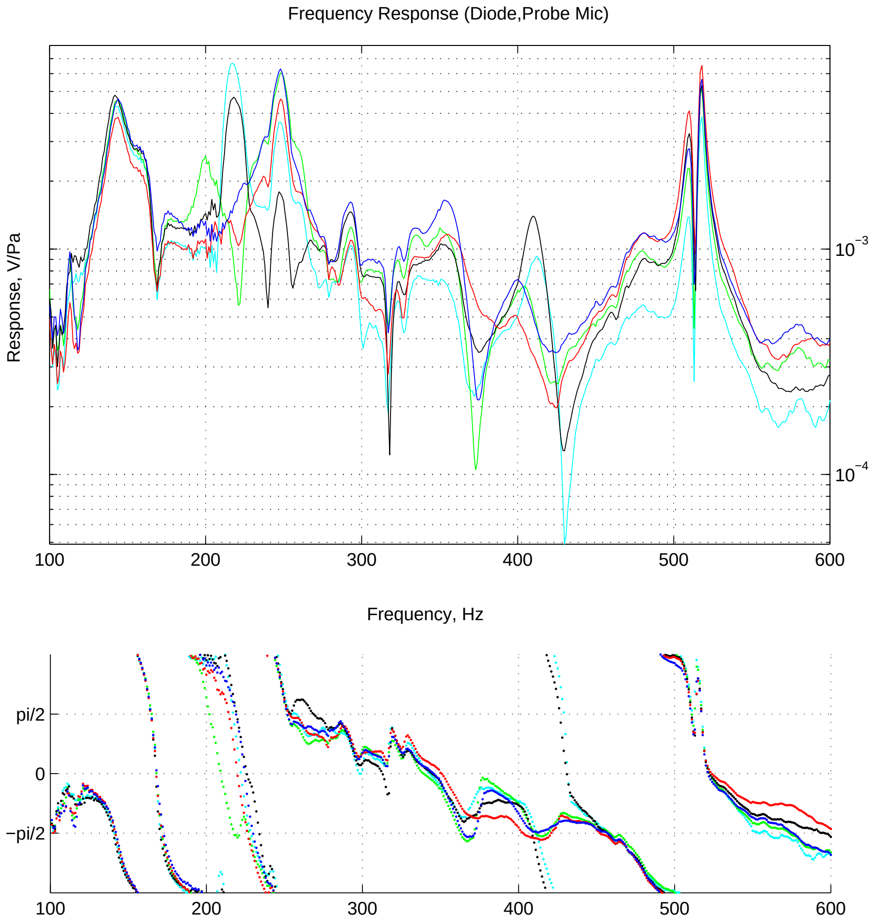


Figure 3.13: Five repeated responses, resetting speaker box position between measurements.

3.4.5 Summary

One possible reason for many of the variations detected is the lack of rigidity in the lips. As they are released (by removing the mouthpiece) and squashed again (by replacing the mouthpiece) they are able to settle into a number of different equilibrium positions. The simple design of the lip guides is not sufficient to prevent this unwanted movement. While they effectively provide support for the lips and to a certain extent they determine the static lip separation, they do not fully constrain the position of the lips. Even without taking the mouthpiece away from the lips it seems that the mouthpiece position is critical. The exact

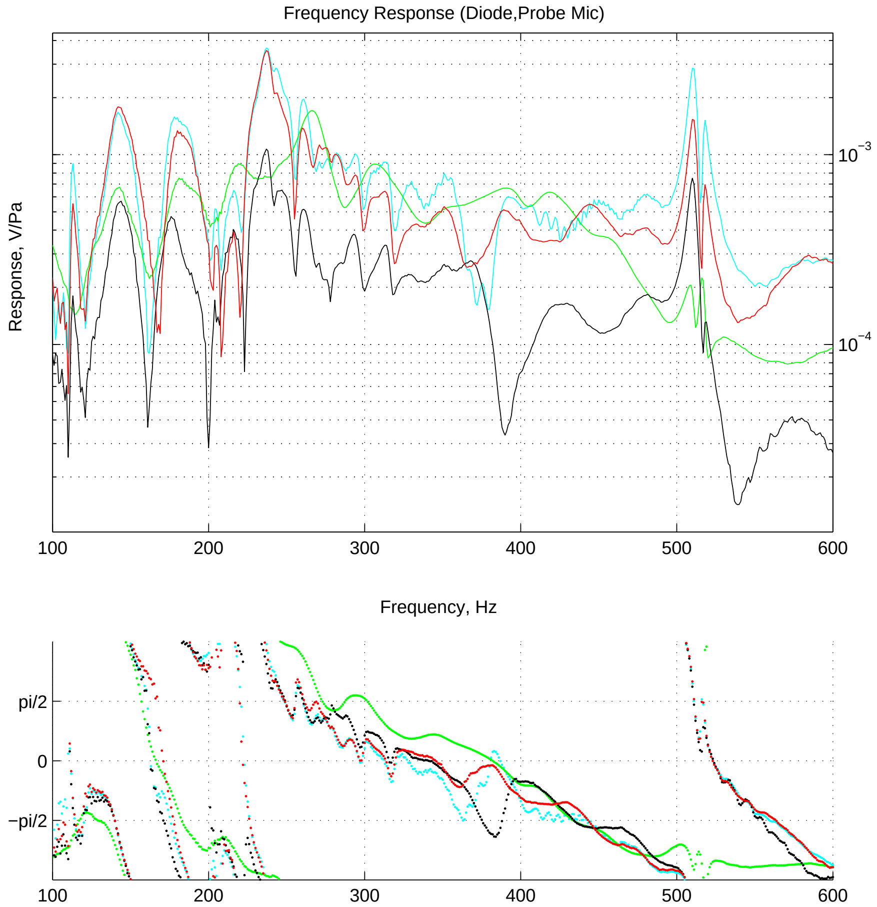


Figure 3.14: Five repeated responses, 'prodding' the lips between measurements.

cause of these variations is unclear but the process of reconnecting the box and mouthpiece seems to 'nudge' the mouthpiece slightly, suggesting that a more rigid mouthpiece support is required.

3.5 Recommendations

It is desirable to avoid as much as possible any movement to the mouthpiece and lips. Ideally the simplest way to achieve this is by not altering any part of the instrument during a set of measurements, but this is obviously not possible when wanting to study differences between instruments. If it is feasible to use the same mouthpiece and retain it in position between measurements then this can avoid many of the sources of unwanted alterations to the embouchure. Improvements to the design of the mouthpiece holder would allow greater confidence in the embouchure stability, this is discussed further in section 3.5.1.

In order to achieve the same embouchure on a number of different occasions or after changing to a different mouthpiece it is necessary to have a specific procedure which causes the lips to settle into exactly the same position. Regularly lubricating the surface of the latex lips with talcum powder can help avoid them ‘sticking’ to the mouthpiece and so being pulled into different positions. However in practice even careful attention to procedure is not likely to be sufficient with the current simple lip-guide design.

3.5.1 Mouthpiece holder

A more rigid mouthpiece support is required in order to have greater confidence in the embouchure stability. The current design of mouthpiece holder relies on blu-tak to seal the mouthpiece cup into the tapered plastic ring. This ring is attached to the mouth by a relatively narrow trolley which rides on two rails.

A new mouthpiece holder has been designed including a removable central section which can be tailored to fit the exact profile of an individual mouthpiece. The mouthpiece is further supported by four plastic screws applying pressure around the shank of the mouthpiece near to mouthpiece cup. This new design is further discussed in section 6.3.3.

3.5.2 Lip-guides

Previous studies with artificial mouths have employed a variety of different methods for guiding the static position of the lips. Designs either constrain the lips inside the mouth cavity [50, 32] or within rigid cylindrical structures [97]. The design of the artificial mouth used in this study was developed by Richards [82] to allow greater access to the lips in order to make changes to the embouchure and to enable a wide variety of instruments to be played. Alternative designs of lip guides (both external and internal) are being developed [75] with the aim of providing more control of the lip position whilst retaining the ease of access and flexibility of a variety of embouchures.

3.6 Conclusions

These results indicate that the frequencies of the resonance peaks are generally well reproduced for repeated resetting of the embouchure parameters. However, the magnitudes and quality factors of the peaks are less well reproduced. Changes to the setup, for example the replacement of an instrument, have been shown to produce significant unwanted changes to the embouchure. Several reasons for this variability, and possible improvements aimed at its reduction, have been discussed. This design of artificial mouth was developed to play a variety of instruments and to more easily allow changes to the parameters that define the embouchure. While gaining this greater flexibility some control has been lost. Improvements to the design of the mouthpiece holder have been detailed. Further improvements have been suggested, particularly to the lip-guide design and these should in the future allow a wide variety of more reproducible embouchures.

Chapter 4

Visualisation of the self-oscillating lips of musicians and the artificial mouth

This chapter begins with an overview of the motivation for these visualisation studies. This is followed by a description of the experimental and analysis techniques used. A qualitative and quantitative comparison of the time variance of the area, height and width of lip opening of real and artificial lips is given in section 4.3. In the following section results are discussed using a definition of a function relating area and height useful in modelling, including a quantitative description of variation with pitch and sound level. The final section of this chapter looks at the special case of extremely loud playing.

4.1 Introduction and motivation

The nature of the motion of the brass player's lips determines the flow of air through the lips, between the player's mouth and the instrument. It is a complicated feedback system in which the motion of the lips controls the air flow, which itself affects the behaviour of the lips.

Several previous studies have used photographic techniques to visualise the motion of brass players lips (Martin[64], Yoshikawa[102], Copley and Strong[30], Vergez and Rodet[95]). These studies have focused mainly on investigating a small range of notes using one player. Elliot and Bowsher [37] have used measurements of mouth pressure and average flow to calculate average values of lip opening for both trombone and trumpet. Recent developments of artificial mouths have led to studies [50, 32, 72, 82] which have used optical techniques to measure the opening between the artificial lips during self oscillation as well as when acoustically driven. Martin[64] and Copley and Strong[30] both presented plots of lip separation against open area; Martin concluded that at high frequencies the area was nearly proportional to the lip central separation, but that the ratio was not constant at large amplitude lower frequency notes. Copley and Strong reported an almost linear relationship between the area and height. None of these previous studies have given quantitative information on the form of the function, $S(h)$, which relates these two parameters.

Here high speed digital photography is used to image the self-oscillating lips of trombone players. The aim of this is to investigate behaviour, primarily variations in the opening between the lips, over a wide range of pitch, sound level and using different players. One aim of this work is to make a comparison of the behaviour of the artificial lips with that of real musicians and hence to provide evidence of the validity of the use of the artificial mouth as a model for real brass players. This investigation also aims to provide experimental evidence to aid the process of refining physical models of the behaviour of the brass players lips, and hence the development of more accurate simulations of brass instruments. One specific aim is to give quantitative information on the form of the area-height function $S(h)$, this is addressed in section 4.4.

4.2 Experimental investigation of lip motion

4.2.1 Experimental procedure

The transparent trombone mouthpiece (see Figure 4.1) developed by Richards[82] was used to allow the lips to be visualised. The design is influenced by those used in several previous studies based on a design by Ayers [4] and is based on the dimensions of a Denis Wick 6BS mouthpiece. It is important that the rim measurements are kept the same as the reference mouthpiece so as to provide the 'correct feel' to the players. The other dimensions were chosen primarily to allow for the robust connection of the individual component parts of the design (namely the junction of the cup and the shank). This resulted in the volume of the transparent mouthpiece being, at 12ml, slightly larger than the reference mouthpiece; it consequently has a lower frequency impedance peak [82]. The mouthpiece is reported (by musicians) to play especially well for the lower regimes, though slightly less well for the higher modes. A King tenor trombone was used for the majority of the experiments.

Figure 4.1: Transparent mouthpiece for trombone

For all experiments the lip motion was filmed using a high speed digital camera (Vision Research, Inc.[98] Phantom v4.1). This allowed a typical capture rate of 5000 frames per second. Image size was generally 512 by 64 pixels for the artificial lips, and 256 by 64, or 128 by 128 for the musicians. The use of the digital high speed camera has several advantages over the use of film and stroboscope.

When using a stroboscope it is necessary to track the playing frequency for synchronisation; this is not needed with high speed filming. Consequently any slight variations in playing frequency are less of an issue; as are any other variations over time as each measurement need only last a fraction of a second. High speed filming allows the visualisation and investigation of transient behaviour, which previously had not been possible.

The main disadvantage compared to using a stroboscope and normal video recording is that a high frame rate necessitates a short exposure time and therefore this technique requires the use of a strong light source. A Schott KL1500 LCD swan-neck lamp was used; this had the benefit of being a cool source so was suitable for use within close proximity to the musicians. The maximum exposure time for this frame rate (180 μs) was used; however it was still necessary to use a relatively large aperture on the camera lens to allow in enough light. This requirement had to be balanced with the need for a reasonable depth of focus to optimise image quality and to avoid the lips moving in and out of focus as they move in the direction perpendicular to the plane of the image.

For the experiments with the artificial lips, the mouth used was based on the design developed by Cullen[32], and modified by Richards[82], as described in section 3.2. The transparent mouthpiece was held in position against the lips using the mouthpiece holder designed by Richards[82]. Here the embouchure was controlled by adjusting the internal lip water pressure, the position of the lip guides and the amount of pressure exerted on the lips by the mouthpiece. For these experiments the embouchure was set and then the note sounded at a moderate to high mouth pressure for several minutes in order to ensure that the embouchure was stable. It is difficult to obtain low notes with the artificial lips. The range of investigation in this study is limited to 150Hz - 220Hz.

Whilst the embouchure of the artificial mouth is on the whole largely symmetrical and the opening easily visualised, this is not the case for many human players. With several musicians there was difficulty in visualising part or all of the opening between the lips due to 'overhang' of the top lip. This was more significant with some players than others and was particularly a problem with high notes where the amplitude of oscillation is small and the overhang increased (previous studies have noted this[64, 30]. This problem could partly be overcome by adjusting the camera angle for each new embouchure, but in practice this proved difficult so limiting the upper range of notes which could be investigated. Players typically sounded notes $\mathrm{B}\flat_1$, $\mathrm{B}\flat_2$, F_3,and D_4 or F_4 at a range of levels nominally *p*, *mf*, and *f* or *ff*. The upper limit of pitches that were possible to analyse depended greatly on the player and the dynamic level played. As measurements were carried out in a laboratory and not an anechoic chamber the sound level was measured on the axis of the bell at a distance of one bell radius so as to minimise the influence of variations in room acoustics. Players were asked to play a note of approximately three seconds duration and the camera was triggered manually to capture part of the steady state of each note. For the measurements with real players it was necessary to apply a low-surface tension liquid (for example a liquid soap such as *Teepol*) to the inside of the optical viewing window of the mouthpiece. This was to prevent the moisture from the players breath from condensing on the surface and obscuring the view of the lips.

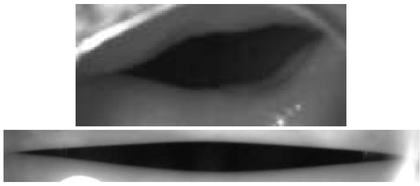


Figure 4.2: Example images from a musician (top) and the artificial mouth (bottom)

Typically the ratio of width to height for the artificial lip opening is $\approx$ 10:1, compared to $\approx$ 4:1 for musicians; consequently the variations in height are less well represented and susceptible to discretisation. To compensate for this Richards[82] filmed only half of the width of the lip opening, and assumed the opening was symmetrical about the centre. This assumption is for the most part reasonable but is less valid for the more ‘relaxed’ embouchures used to play lower notes; therefore it was decided to film the complete opening.

4.2.2 Analysis procedure

Each of the high speed digital films was edited to give a series of images, typically 200 frames, including several cycles of oscillation of the lips. These individual frames were cropped to leave just the area of interest so reducing the data size and hence the analysis time. Figure 4.3 shows examples of images obtained.

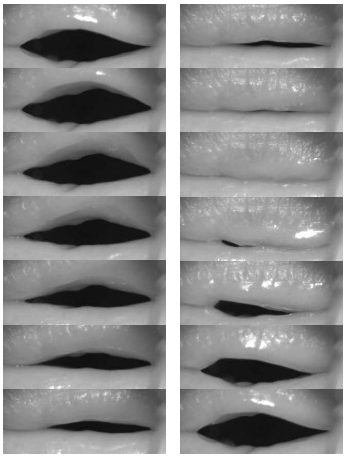
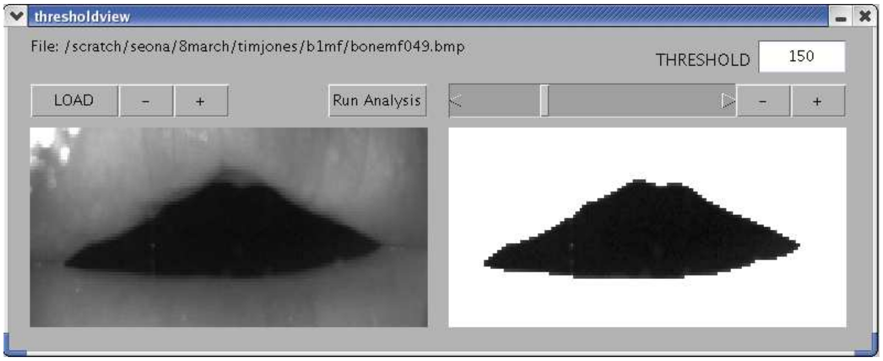


Figure 4.3: Example images from one cycle

Each series of images was then analysed in Matlab using a script designed with a Graphical User Interface (see figure 4.4). The interface allows viewing of the original image alongside a ‘thresholded’ image, whilst adjusting the threshold value. By this process a pixel threshold level was manually chosen to isolate the open area from the lip images as demonstrated in Figure 4.5. The value varied from one data set to another due to variations in the quality of the lighting, including the presence or absence of shadows on images and teeth visible within the



thresholdview

File: /scratch/seona/8march/timjones/b1mf/bonemf049.bmp

THRESHOLD 150

Figure 4.4: The graphical user interface in Matlab allows viewing of the original image alongside a ‘thresholded’ image, whilst adjusting the threshold value. Following the selection of the threshold level the further analysis steps are then carried out by selecting the ‘run analysis’ button which calls the image analysis program.

open area. In some extreme cases it is necessary to manually ‘correct’ the images containing particularly obvious teeth. Following the selection of the threshold level the further analysis steps are then carried out using code also written in Matlab. Using a loop, each image in the series is examined in turn. For each image a further loop looks at each pixel column by column and compares the value to the chosen threshold level. For each pixel determined to be ‘open’ (ie darker than the threshold) the area count is increased. The open height at each column is determined to be the count of the number of ‘open’ pixels in that column, see figure 4.6. Similarly the width is determined to be the number of columns containing an open pixel. The value for the maximum and (spatial) mean height

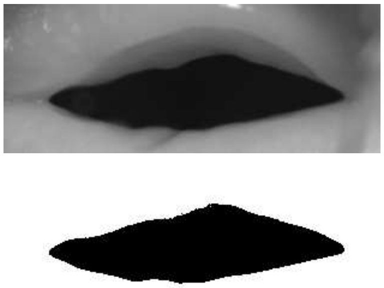


Figure 4.5: Example lip image and the corresponding ‘thresholded’ image

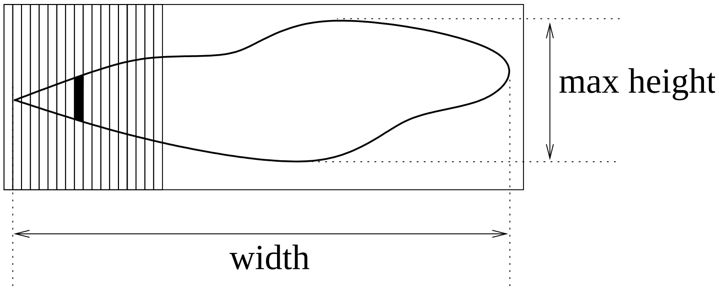


Figure 4.6: Illustration of the image analysis process where the open height is determined for each column of pixels across a particular image. The maximum and (spatial) mean height for that image are then calculated from the set of values.

are then calculated using the full set of individual height values across the width of each image. In this way a count of number of open pixels was obtained for each image before moving on to the next image in the series. After all images are analysed this results in data for the maximum and mean heights, width, and total area (in pixels) as a function of frame number. A calibration image was taken (see Figure 4.7) using graph paper wrapped around the lip of the player. This allowed a calibration of pixels to mm to be obtained and entered into the analysis. The frame rate is also entered.

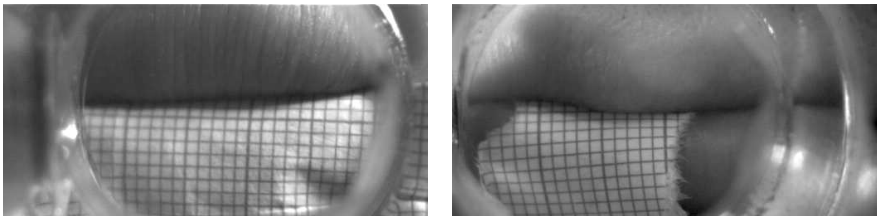


Figure 4.7: Example calibration images

4.2.3 The definition of height

Initial experiments with the artificial mouth [82] have defined $h(t)$ as the maximum lip separation. This is an effective definition if the vibrations of the lips display behaviour which is essentially a modulation of the vertical scale of the aperture. However as can be seen in the example given in Figure 4.3, the brass player's lips undergo very complicated movements, where often the maximum height is not an appropriate measure of the overall lip separation. In this study we have explored the use of the mean height as an alternative definition of $h(t)$. This effectively simplifies a complicated shape where different sections of the lips are moving in different ways to a rectangle of time varying width and height (see Figure 4.8).

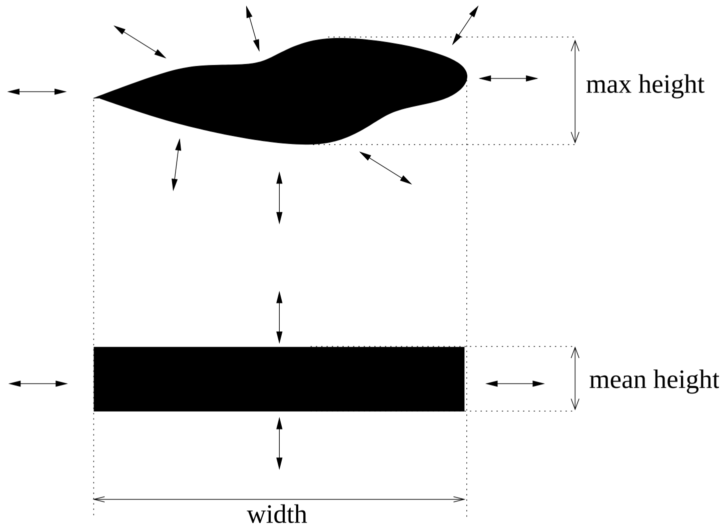


Figure 4.8: Illustration of simplification of a complicated shape where different sections of the lips are moving in different ways, to an equivalent rectangle of time varying width and height.

4.2.4 Accuracy

The effect of the player

The variability inherent in measurements obtained from the musicians means there are some slight discrepancies in the pitch of notes and differences between the sound levels of nominally equivalent dynamic levels. For example when two players are asked to play the note B$\flat_1 mf$ one may produce a sound level of 98dB and another player may play slightly louder at 102dB. This variation should be noted particularly when making direct comparisons between players.

Visualising the opening

As described in section 4.2.1, it is not always easy to visualise the lip opening. Part of the experimental and analytical process involved discarding films that were on inspection obviously not showing the true opening. Some films, particularly high pitch low sound level notes, where the overhang of the top lip is significant causes the data for the opening part of the cycle to be less reliable. It is hard to quantify the effect of this issue but it is estimated that this is the most significant source of error in the measurements of the smallest amplitude lip openings.

Calibration accuracy

The calibration, of pixels to millimetres, was obtained using reference images as shown in figure 4.7. The error on the calibration values is estimated to be approximately 2%. This is most significant when comparing results from different players and different experimental sessions where a different calibration is used.

Alignment of lip opening

Variations in embouchure and in some cases the constraints of the experimental setup mean that the image boundaries are not aligned exactly with the lip opening (see example image in figure 4.9. In most cases the alignment is within 2 or 3 degrees, and even the worst examples are at most rotated by 12 degrees from alignment. As the analysis procedure measures width horizontally and height vertically within the image boundaries any misalignment is a source of error in the measurements obtained. In most cases the correction factor is very small and even in the worst examples (rotated by 12 degrees from alignment) this equates to a 2% over estimate of height and 2% under-estimate of width. The area measurements are unaffected.

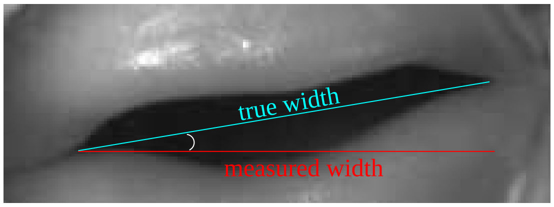


Figure 4.9: Illustration of lip opening not exactly aligned with the image boundaries. Angle is 10 degrees which equated to a 1.5% over estimate of height and 1.5% under-estimate of width.

Determining the lip boundaries - choice of grey level threshold

The Graphical User Interface for the analysis program allows easy testing of different grey level threshold values before running the analysis program. The choice of threshold value does affect the exact areas and heights measured as the lip edges are not a sudden change from black to white but shades of grey. This is obviously more significant for small openings than large. The error in the linear measurements (maximum height and width) is estimated to be ± 1 pixel which is equivalent to between ± 0.06 mm and ± 0.121 mm.

Summary

It is believed that due to the combination the various sources of uncertainty the linear measurements (height and width) are in most cases precise to the nearest 0.2 mm and the area measurements to the nearest 1 mm^2.

4.3 Describing the lip opening

Many insights can be gained from qualitative and quantitative descriptions of the characteristics of lip motion of the brass player. The observed motion of the lips is often seemingly very complex with motion both in the plane of the lip opening and perpendicular to that plane. It is necessary to make certain simplifications in order to enable quantitative descriptions of the observed behaviour. Visual inspection of the raw films often suggests the presence of secondary transverse waves moving along the lip and other such higher order oscillations, investigation of which is beyond the scope of this study. Here, only the two-dimensional motion in the plane of the lip opening is described as observed in videos obtained as detailed in section 4.2.1. The analysis procedure presented in section 4.2.2 provides data for the area, width, and the maximum and mean height of the lip opening as a function of time. In section 4.3.1 the time-averaged behaviour is presented. This is followed by the results of analysis of variations within each cycle given in section 4.3.2.

4.3.1 Time-averaged behaviour

Previous studies have noted that as expected the amplitude of lip motion increases with increasing sound level but decreases with increasing frequency [64, 30, 37]. Inspection of the raw films alone is sufficient to confirm this general behaviour is evident.

One characteristic parameter of an embouchure is the time averaged lip separation h_0 (see figure 4.10); calculated from the mean value of the lip opening mean-height (as defined in section 4.2.3) over a number of complete cycles. This quantity may be equal to the amplitude of the maximum lip displacement if the lips just close once.

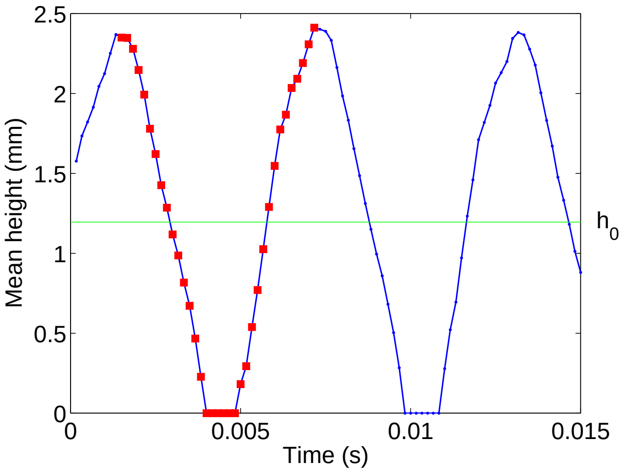


Figure 4.10: The time averaged lip separation, h_0, is the mean of the lip separation (calculated over a complete cycle).

Elliott and Bowsher[37] used measurements of steady pressure in the player's mouth and average flow in the throat of the instrument to calculate the "average resistance" of the lip opening. By assuming a rectangular slit opening they were also able to compute values of the "average" lip separation for a range of notes at a *mf* level. These calculated values show a reduction in lip opening with increasing frequency of the note played. Figure 4.11 gives time-averaged values of the measured lip separation as a function of frequency. For each measurement (a single note by a single player) the value of the mean lip separation, h_0, is calculated over an integer number of complete cycles of oscillation. Then, using results from five different players, the mean and standard error on the mean is calculated for each note (of the same pitch and nominal dynamic level for example B$\flat_1$*mf*) to produce the plotted data points and associated error bars. Calculated data from Elliott and Bowsher [37] is also plotted for comparison. Magnitudes and variation with frequency and sound level agree with previous studies [64, 37, 30]. The error bars give some measure of the variations in the magnitude of the lip oscillation between players. For simplicity the data is grouped into three sets for the dynamic levels *p, mf, ff* as played. As discussed in section 4.2.4 for any given dynamic level there was some variation in the actual sound level produced

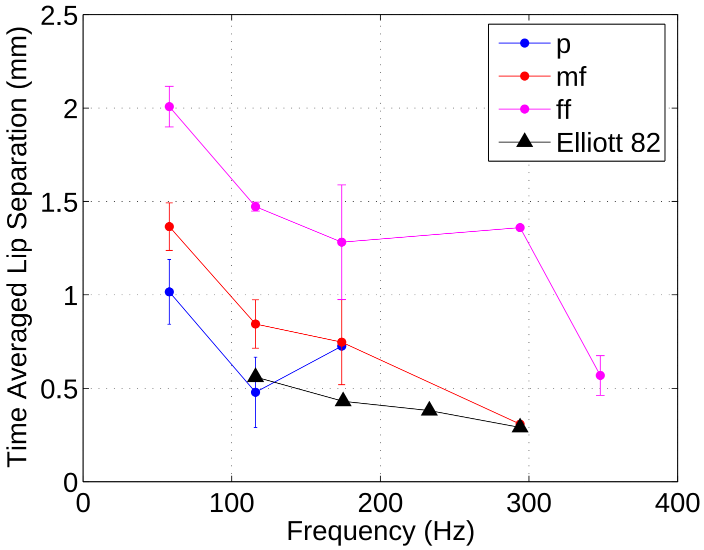


Figure 4.11: Mean and standard error (using data from five different players) of h_0, the time averaged lip separation, as a function of frequency. Also showing calculated data from Elliott and Bowsher [37]

by different players and this may account for some of the spread of the data presented here. Only a single value is presented for the note F_3 *p* as for most players it was not possible to visualise the lip opening for high pitched low sound levels such as this. The value of h_0 for this note is larger than might be expected as, although the amplitude of the oscillation is very small (a fraction of h_0), the lips do not close completely at any point in the cycle giving a similar value of h_0 as seen for the *mf* level.

Figure 4.12 again gives time-averaged values of mean lip separation; this time as a function of sound level using data from one particular embouchure on the artificial mouth playing the note E_3. Also presented are two data points from alternative embouchures also playing the note E_3 for comparison. The observed increase in the time averaged lip separation, h_0, with increasing mouth pressure is close to linear as shown in figure 4.13.

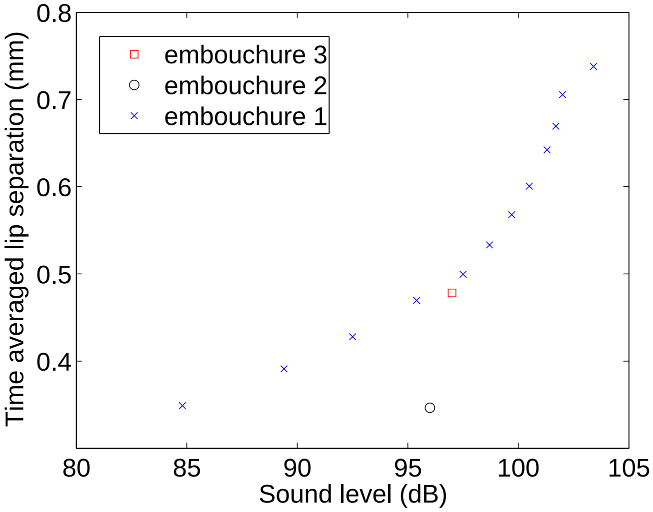


Figure 4.12: Values for h_0, the time averaged lip separation, as a function of sound level obtained using the artificial mouth playing the note E_3

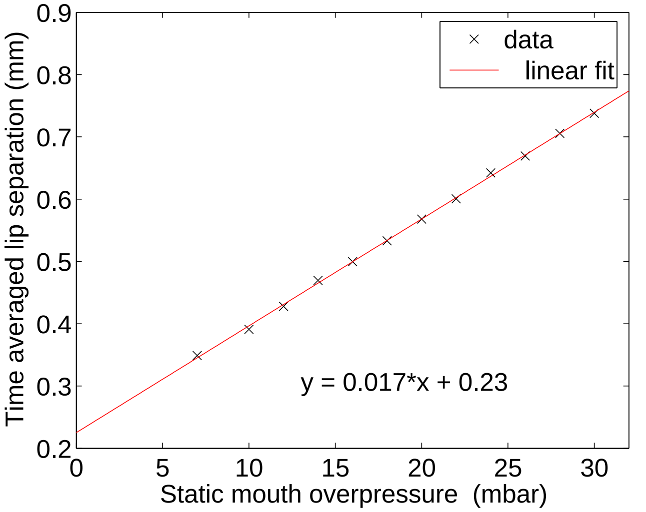


Figure 4.13: Values for h_0, the time averaged lip separation, as a function of static mouth overpressure for the artificial mouth playing the note E_3 and linear fit to the data.

4.3.2 Variation of lip opening with time

A typical plot of area, height and width against time is given in figure 4.14. The data for the height and area of the lip opening show generally smooth variations over the course of each cycle of oscillation. The width of the opening often varies

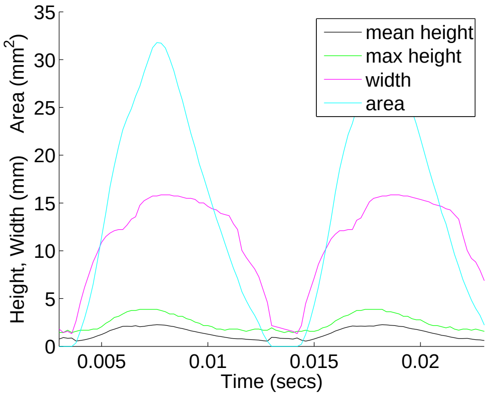


Figure 4.14: Area, height and width as a function of time.

less smoothly with regions of almost constant value at maximum opening. The lips close, or almost close, once during each cycle in all but a few cases (some very quiet notes) and the motion is approximately sinusoidal in agreement with previous studies [64, 30].

Variation between players

Figure 4.15 shows two sets of results for the note B$\flat_1$ played *mf* by two different musicians. It can be seen that two players have different characteristic shapes

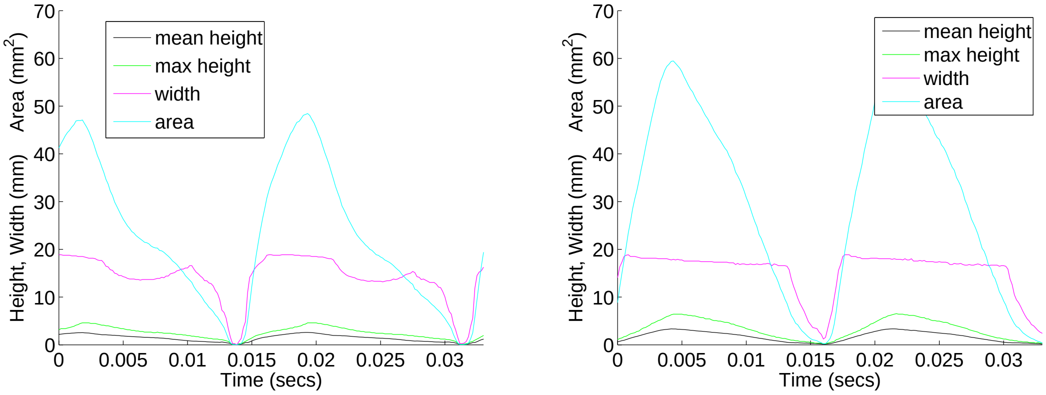


Figure 4.15: Area, height and width as a function of time for the note B$\flat_1$*mf* sounded by two different players.

to the curves of area, width and height and also that the magnitudes of these parameters differ slightly between players. Some of the differences in magnitudes may be due to slight discrepancies in the sound level of nominally equivalent dynamic levels, as discussed in section 4.2.4. Overall the general behaviour seen is consistent over the range of players.

Figure 4.16 shows two sets of results for the note B$\flat_2$ played *mf* by a musician and the artificial mouth. As in figure 4.15, the two sets of results show different characteristic shapes to the curves of area, width and height and also that the magnitudes of these parameters differ slightly. The width to height ratio of the lip opening (as discussed in section 4.2.1) is noticeably larger for the artificial mouth.

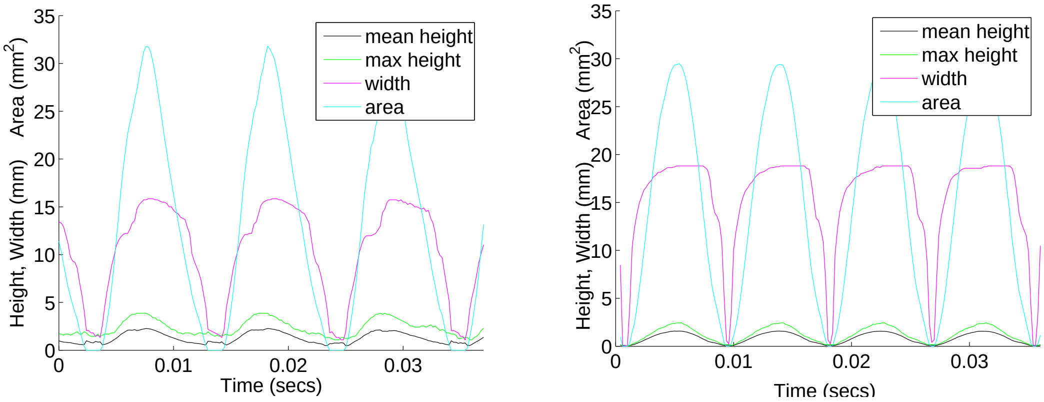


Figure 4.16: Area, height and width as a function of time for the note B$\flat_2 mf$ sounded by a musician (left) and the artificial mouth (right).

Figure 4.17 shows three sets of results for three different embouchures of the artificial mouth playing the same note, E_3, at approximately the same sound level 97±0.5dB (approximately *mf* level). These three embouchures each required different mouth pressures to produce the same sound level. As with the results (above) for different players, there are small variations in the shape of the curves but the overall behaviour is consistent.

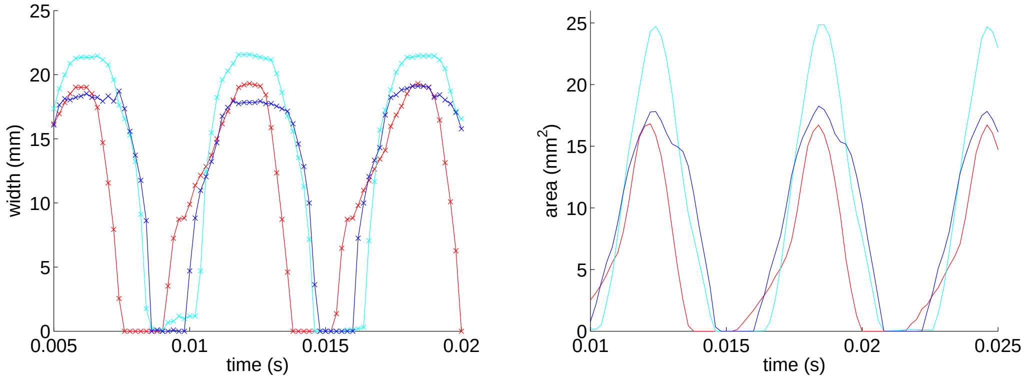


Figure 4.17: Three different embouchures of the artificial lips, playing the note E_3. On the *left* is a graph of width as a function of time and on the *right* is a graph of open area as a function of time.

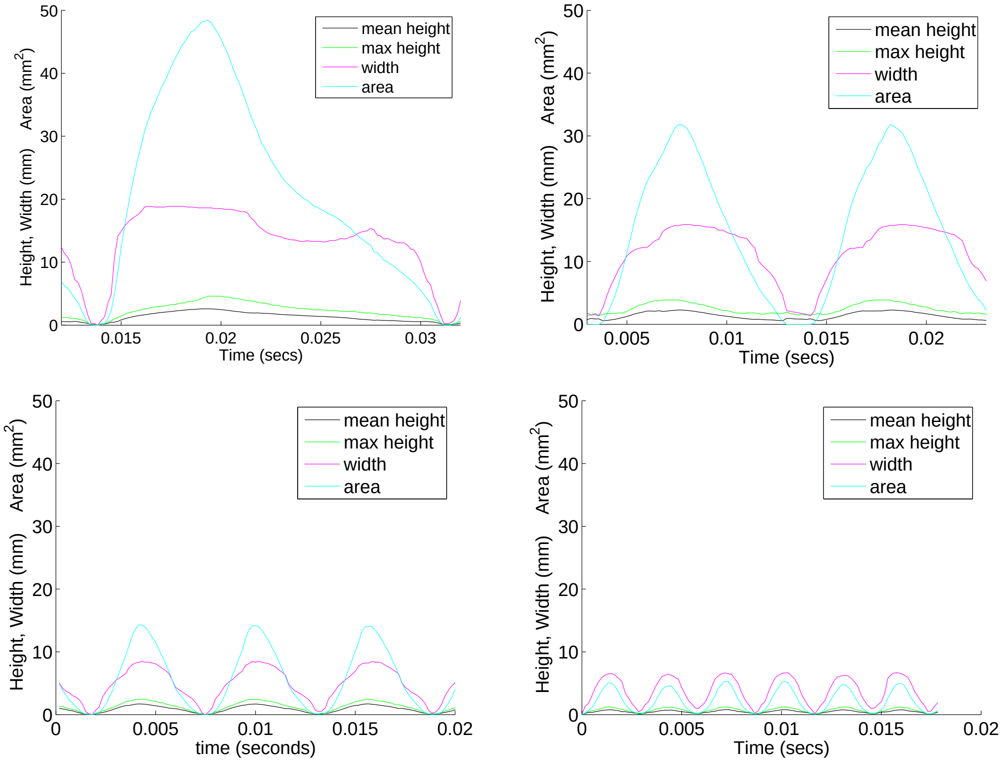


Figure 4.18: Area, height and width as a function of time, Player A notes $\mathrm{B}\flat_1 mf$ (top left) $\mathrm{B}\flat_2 mf$ (top right), $\mathrm{F}_3 mf$(bottom left) $\mathrm{F}_4 mf$ (bottom right)

Variation with changes in pitch

Figure 4.18 shows graphs of area, height and width of the lip opening as a function of time for one player (A) sounding four notes $\mathrm{B}\flat_1$ $\mathrm{B}\flat_2$, F_3, and F_4 at the same dynamic level *mf*. These results show the expected decrease in amplitude with increasing frequency of the note played. It can be seen that the size of the regions of constant width at maximum opening also vary with frequency, being most significant for the lowest frequency note and becoming less so as the frequency rises.

Variation with changes in sound level

Figure 4.19 shows graphs of open area as a function of time for (left) three dynamic levels, Player A, note $B\flat_1$ and (right) results from the artificial mouth from just one of the three embouchures shown in 4.17, playing at several sound levels. In both sets of results the overall amplitude of the opening increases as the sound level increases (and also therefore for the same note the slope of the curve is steeper). Both graphs show that the 'bumps' which are sometimes seen in the higher amplitude motion of the lips gradually develop from a relatively low sound level. The asymmetry in the opening and closing portions of the cycle also becomes more noticeable with increasing sound level.

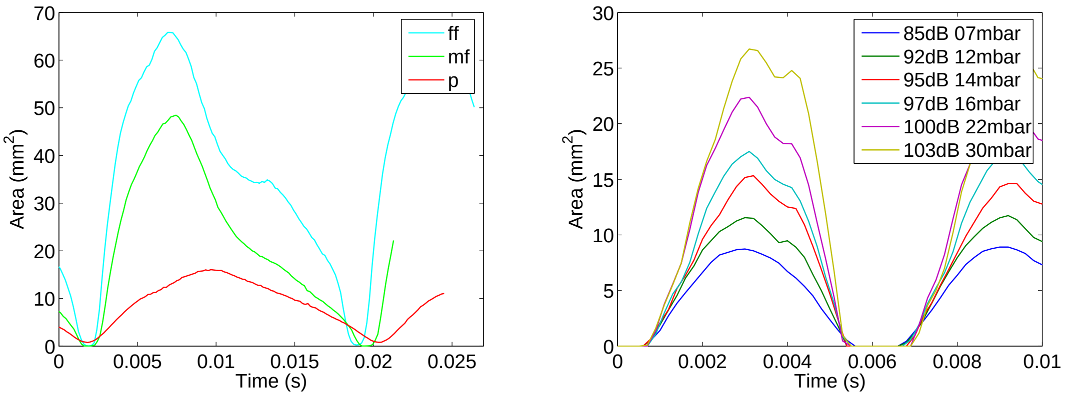


Figure 4.19: On the *left* is a graph of area as a function of time for player A showing results form three dynamic levels of the note $B\flat_1$. On the *right* is a graph of area as a function of time for the note E_3 played by the artificial lips, at a number of dynamic levels.

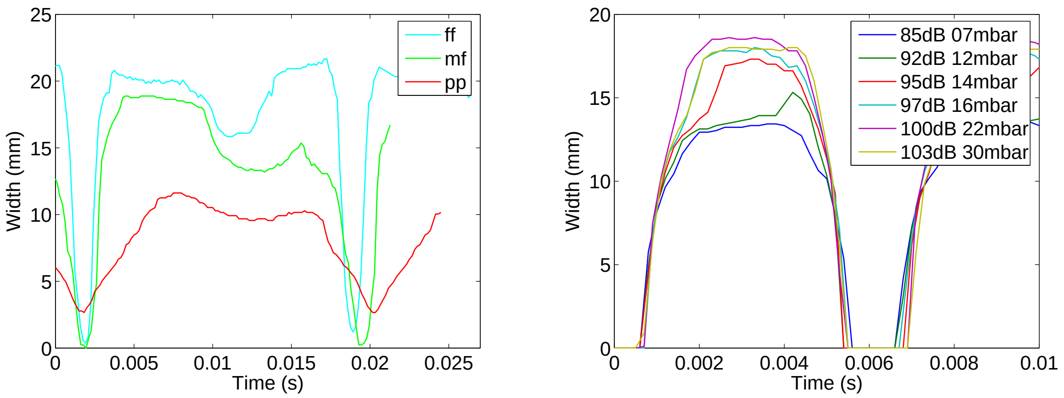


Figure 4.20: On the *left* is a graph of width as a function of time for player A showing results from three dynamic levels of the note B$\flat_1$. On the *right* is a graph of width as a function of time for the note E_3 played by the artificial lips, at a number of dynamic levels.

Figure 4.20 shows the width of lip opening as a function of time for different dynamic levels. The results from the musicians show that the size of the regions of approximately constant width vary with sound level. For the results on the left of figure 4.20 the proportion of the cycle where the width is approximately constant varies from 80% at *ff*, down to 74% at *mf* and down to 49% of the cycle for quietest level, *p*. The results from the artificial mouth also show similar regions of constant width but the extent to which this varies with sound level is less clear.

It is likely that the rim of the mouthpiece has a constraining effect on the lips and therefore produces these regions of constant width. For the lowest pitched loudest notes the maximum width is close to the internal diameter of the mouthpiece, 25mm. For higher pitched notes the amount of lip present within the rim of the mouthpiece is usually greater, and the lip tension is also increased meaning that the maximum possible width will be smaller. Often the lip opening is positioned away from the centre of the mouthpiece so the internal space is less than 25mm. Two example images showing the maximum width of the lip opening are given in figure 4.21.

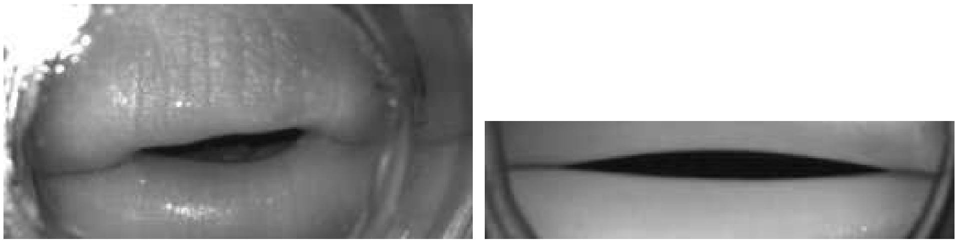


Figure 4.21: Maximum width of the opening of the lips of (*left*) player TJ playing the note B$\flat_2$ at *mf* and (*right*) the artificial mouth playing note E_3 at 97dB

4.3.3 Summary

Investigation of the behaviour of the lip opening has shown, as expected, the amplitude of lip motion increases with increasing sound level but decreases with increasing frequency. This is in agreement with the results of previous studies [64, 30, 37]. There are also as expected variations in the magnitude of the lip oscillation between players, and between different embouchures on the artificial mouth. The variations in the height and area of the lip opening are generally smooth over the course of each cycle of oscillation. The width of the opening often varies less smoothly with regions of almost constant value at maximum opening. The extent to which this behaviour is evident depends both on the pitch and sound level of the note being played; being most obvious for low pitched loud notes, and becoming less so with increasing pitch or reducing sound level. Some differences have been identified between the behaviour of the artificial lips and that of the lips of musicians, however the general features of behaviour are reproduced by the artificial mouth.

4.4 The area-height function - towards a more realistic model

Section 2.5 presented a system of three equations used to describe the playing behaviour of a brass instrument. Important parameters in this description of the player's lips include the displacement of the lips from their equilibrium position, the height $h(t)$, and the open area $S(t)$, which determines the acoustic volume flow. An accurate description of the area as a function of height $S(h)$ will support the development of realistic simulations of lip behaviour and hence brass instruments sound.

Many models of lip motion (for example [3, 37, 87]) have simplified the lip aperture to a rectangle of constant width and varying height, giving the linear relationship $S(t) \propto h(t)$. A recent physical model [66] has instead used a quadratic relationship $S(t) \propto h(t)^2$ with good results in terms of realistic sound output. By assuming a relationship of the form $S(t) \propto h(t)^q$ a general area-height function can be defined:

$$S(t) = S_0[h(t)/h_0]^q \tag{4.1}$$

where S_0 and h_0 are reference values for the open area and height respectively, and where the exponent q takes a value of either 1 or 2 for the two simple cases described above. Initial experiments using an artificial mouth [82] have suggested that the true behaviour is somewhere between these two cases. The nature of this relationship between lip opening area and height is further investigated here using the results of a series of experiments with actual musicians and further results from the artificial mouth. A logarithmic plot of area $S(t)$ against height $h(t)$ yields a value for the exponent q from the gradient of a straight line fit.

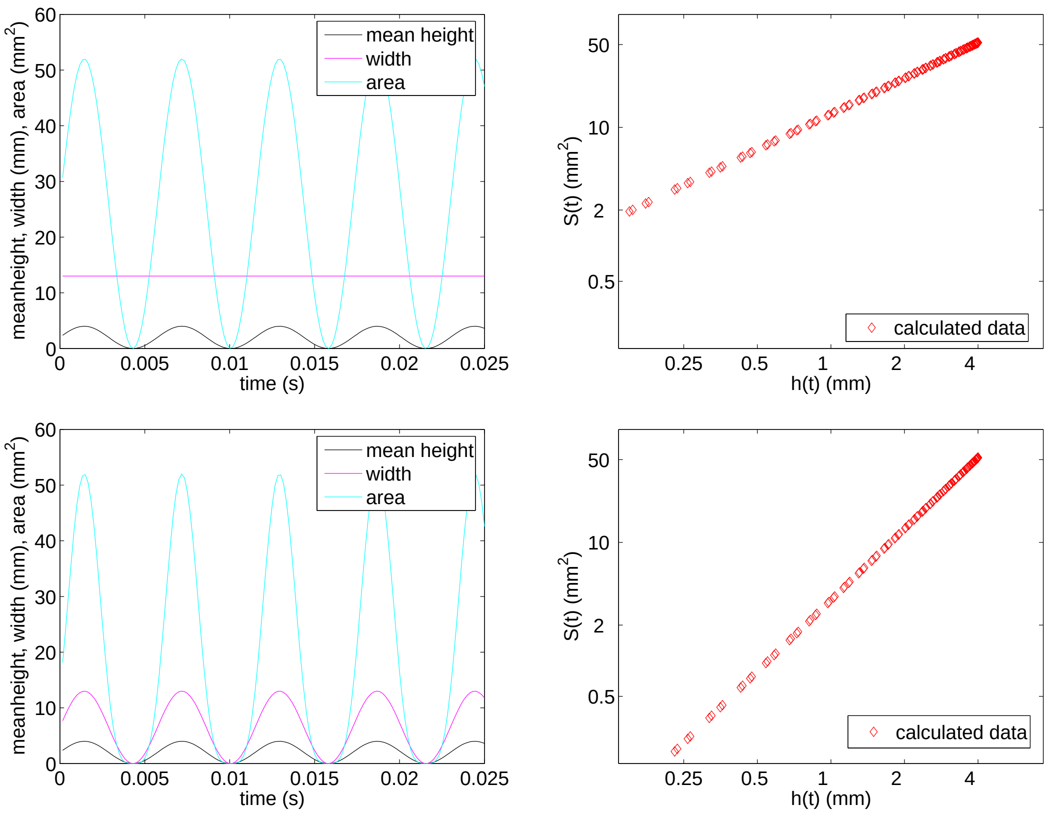


Figure 4.22: Two different theoretical cases determined by the form of width as a function of time. The first case (upper graphs) is constant width, the second case (lower graphs) is width varies sinusoidally in phase with the height. On the left are plots of calculated area using sinusoidal variations in mean height with time. On the right are logarithmic area-height plots showing slopes of 1 and 2.

Figure 4.22 gives calculated data for two different theoretical cases determined by the behaviour of the width of the opening as a function of time. In both cases the mean height varies sinusoidally with time and by assuming a rectangular opening the area of the opening is calculated from the mean height multiplied by the width. The first is the linear case where the width is constant and the logarithmic area-height plot gives a slope of one. The second is the quadratic case where the width varies sinusoidally in phase with the height and the logarithmic area-height plot gives a slope of two.

4.4.1 Sensitivity of results to analysis procedure

Definition of height $h(t)$

As mentioned previously in section 4.3 the lip motion is in many cases very complicated and often the maximum height of lip separation is not an effective measure of the overall behaviour of the lip separation.

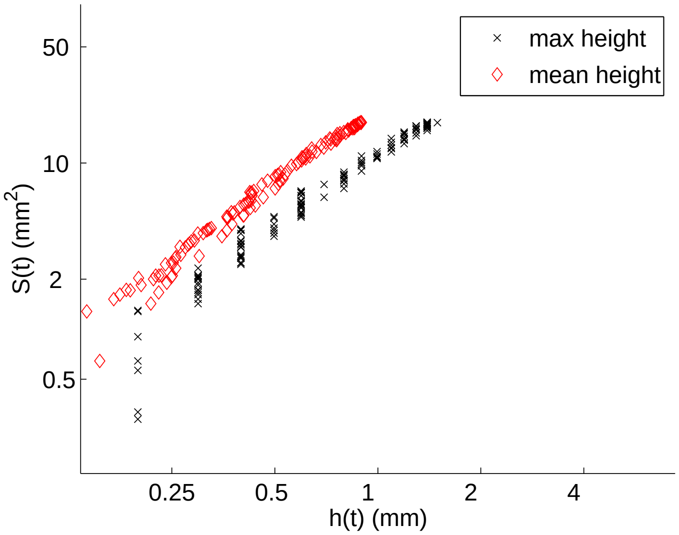


Figure 4.23: Logarithmic area-height plot showing use of mean height giving less curvature at high amplitudes. Artificial mouth, E_3

Figure 4.23 shows results using both maximum and mean height. Due to the limited image resolution there is significant discretisation of the maximum height data and hence several values of area correspond to the same value of maximum height. The mean height is calculated from many separate height measurements averaged over the full width of the lip opening. This definition results in an improvement in height resolution and produces more detail in the area-height plot. Curves are also generally more regular showing in particular a reduction in the deviation from a straight line at high amplitudes. This appears to be due to specific behaviour during this portion of the cycle where the ‘tip’ of the lip often moves quite dramatically, so causing the maximum height to vary much more significantly than the mean height. The same reasoning explains the reduction in the severity of the observed hysteresis effect as shown in figure 4.24.

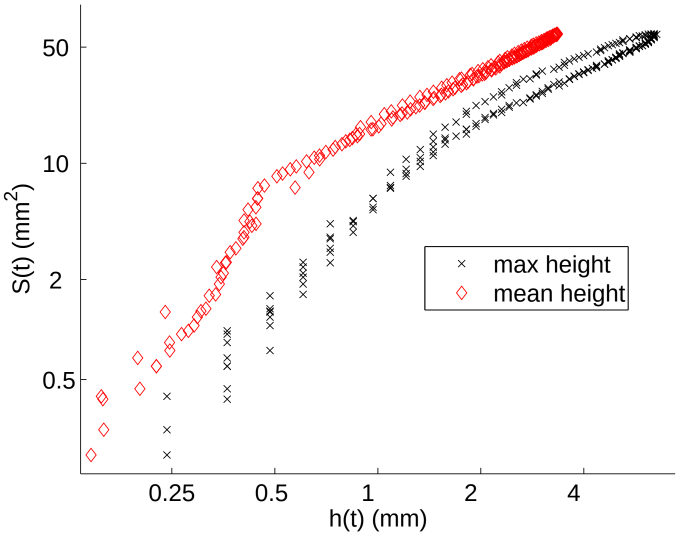


Figure 4.24: Logarithmic area-height plot showing reduced hysteresis with use of mean height and less curvature at high amplitudes. Player S, note $B\flat_1 mf$

There is some slight discrepancy between the exponents obtained using the two different definitions but this is mainly attributable to the improvements in line fitting due the factors mentioned above. Therefore in order to simplify the description of behaviour the mean height definition of $h(t)$ is used for the remainder of this study. Where reference is made to height $h(t)$ it is the mean height that used, as described in section 4.2.3

Choice of the range for a straight line fit

Many data sets have 'noise' present at very low amplitudes due to the low accuracy achievable when imaging very small regions of lip opening. Where the lip separation is less than 0.2mm and equivalent to only 1 or 2 pixels the error is of the same order as the measurement itself and therefore this data is excluded before fitting a straight line.

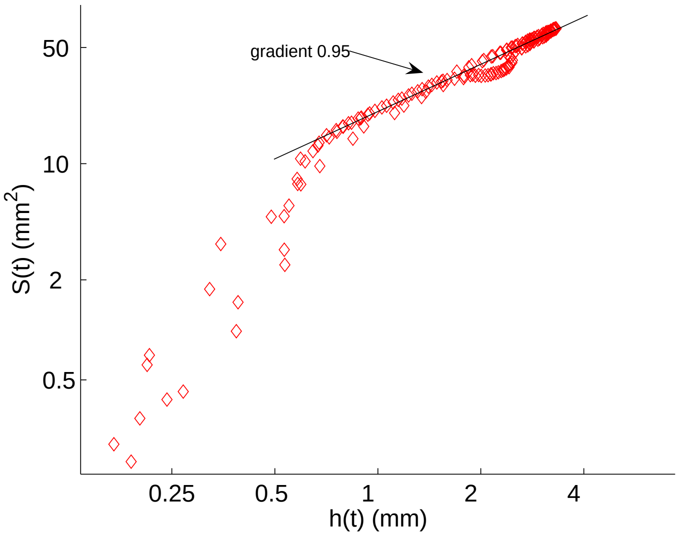


Figure 4.25: Logarithmic area-height plot showing variations in slope and scatter at low amplitudes (below approximately 0.7mm). Player A, note B$\flat_1$*ff*

Some data sets do not support a straight line fit over the full range of heights and areas. In particular some low pitched notes played by musicians at moderate to high sound levels show clear variations in the gradient including an apparent degree of scatter in the low amplitude data. In these cases the fit is only applied to the linear part of the data as a simple approximation providing a description of the behaviour seen in the majority of the cycle. Figure 4.25 is a typical example of this. In addition a small number of results show significant hysteresis giving two distinct lines of data and in these cases separate gradients are determined as shown in figure 4.26.

Choice of threshold value and other sources of error

The accuracy of the area and height data is discussed in section 4.2.4. Sources of error considered (including the choice of threshold level, the calibration, alignment of the image) whilst affecting the values of the height and area have little or no effect on the gradient of the graph (which gives the value of the exponent q).

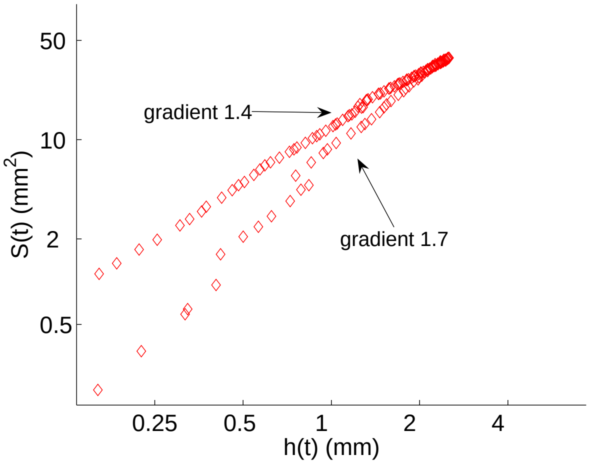


Figure 4.26: Logarithmic area-height plot showing two distinct slopes. Player M, note A_1p

For this reason only the gradient of the straight line fit is quoted and not the intercept. Figure 4.27 shows examples of this.

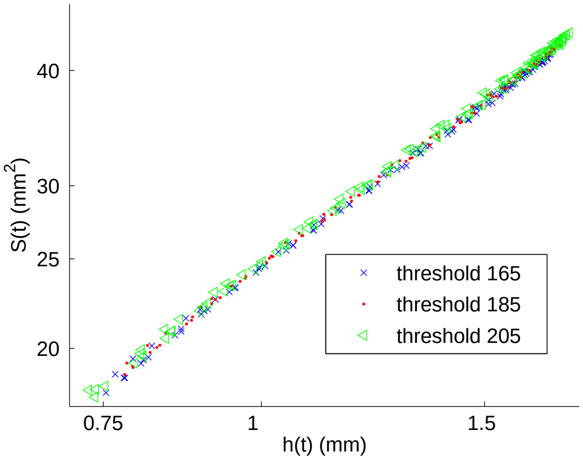


Figure 4.27: Logarithmic area-height plot using three threshold values. Straight line fits give the same gradient for each data set.

Summary

It is clearly important to consider the most appropriate range of data over which to apply the straight line fit in order to give the best representation of the behaviour. In section 4.4.2 an overall value is given from a single straight line fit representing the behaviour over the majority of the cycle; where this is clearly not appropriate a range of values is given. In section 4.4.3 this issue is further investigated and distinct regions of behaviour are identified. This method allows a more complex description of the area-height relationship to be developed.

4.4.2 Results - single straight line fit

In this section an overall value of the exponent q is presented as obtained from a single straight line fit, using the least squares method. Values for the exponent q are given to 2 significant figures; this level of accuracy is achieved only within the regions over which the fit has been applied.

Results obtained from the experiments with musicians yield values for the exponent q ranging from just below 1 to over 2. The results presented in tables 4.1 and 4.2 are from a single player and illustrate examples of all the main trends identified. Though there are differences in the exact values of the exponent q between players, the behaviour described below applies to all players investigated. Further examples are given in appendix A. The results for the artificial mouth give values for the exponent q in the range 1.0 to 1.6 and in general show less complex behaviour such as less hysteresis and less significant variations in the gradient within a single data set.

Effect of change in pitch - musicians

As the pitch of the note played rises the value of the exponent q increases. At a *mezzo-forte* level the value of the exponent q increases with rising pitch from close to 1 for the note $B\flat_1$ to close to 2 for the note F_4. Values for the exponent q are given in table 4.1 and two example plots are given in figure 4.28(a) for the note $B\flat_1$ *mf* and figure 4.28 (b) for the note F_4*mf*. This increase in q corresponds to a decrease in the amplitude of oscillation from low to high pitched notes.

Table 4.1: Example results - player A

Note	Dynamic	level (dB)	q
$B\flat_1$	*mf*	98	1.2
$B\flat_2$	*mf*	95	1.3
F_3	*mf*	97	1.6
F_4	*mf*	109	1.9(1.5-2.5)

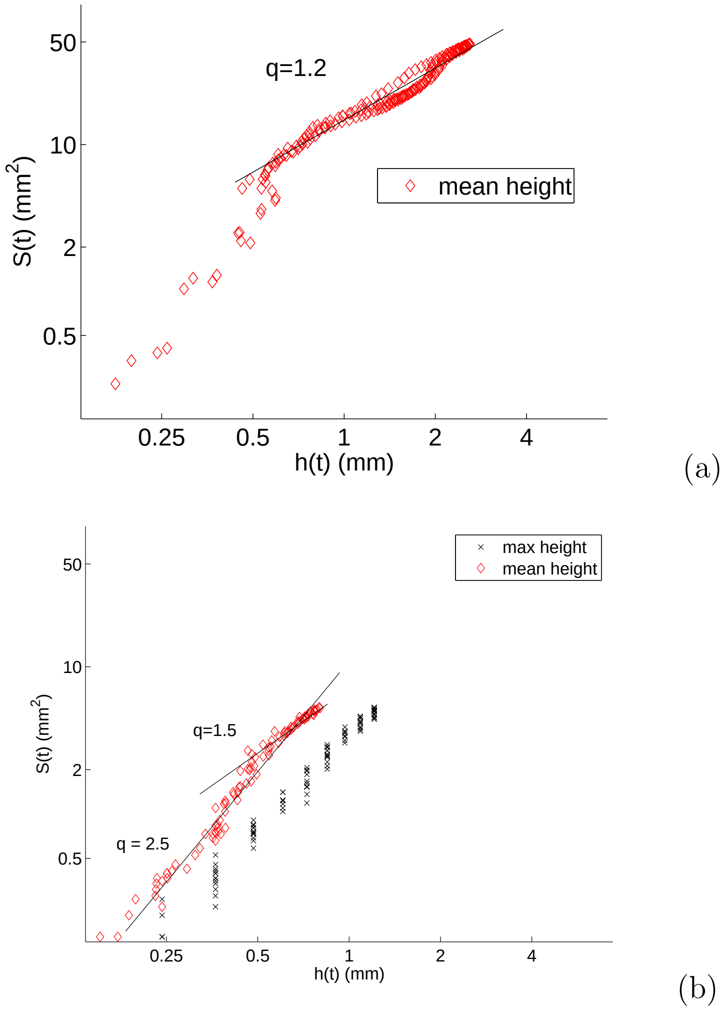


Figure 4.28: Logarithmic area-height plot showing Player A, (a) note $B\flat_1$ *mf* and (b) note F_4*mf*

Effect of change in pitch - artificial mouth

There is some trend towards higher q values (up to $q = 1.6$) for some of the higher frequency notes, and lower q values($q = 1.3$) for some of the lower notes investigated but the range of values of the exponent q is not as great as with the musicians. Figure 4.29 shows results from two notes played using two different embouchures but sounding at the same level (97dB). The limited frequency range available with the artificial lips may be the reason why it is not possible to achieve the full range of behaviour seen in the results from the musicians. See appendix A for further example results.

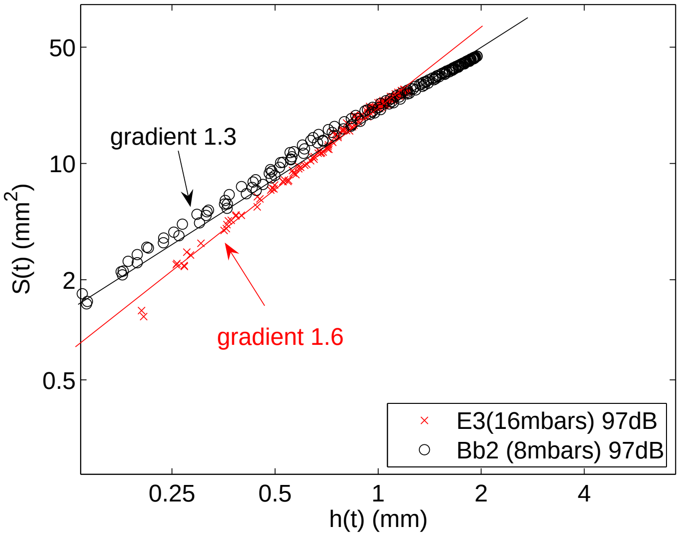


Figure 4.29: Logarithmic area-height plot artificial lips B♭$_2$ and E$_3$ at 97dB

Effect of change in dynamic level - musicians

As the dynamic level of the note played decreases the value of the exponent q increases. Three data sets are given in figure 4.30 showing results for the note B♭$_1$*ff*, *mf*, and *p*. Again this increase in q corresponds to a decrease in the amplitude of oscillation from loud to quiet notes. Further examples are given in

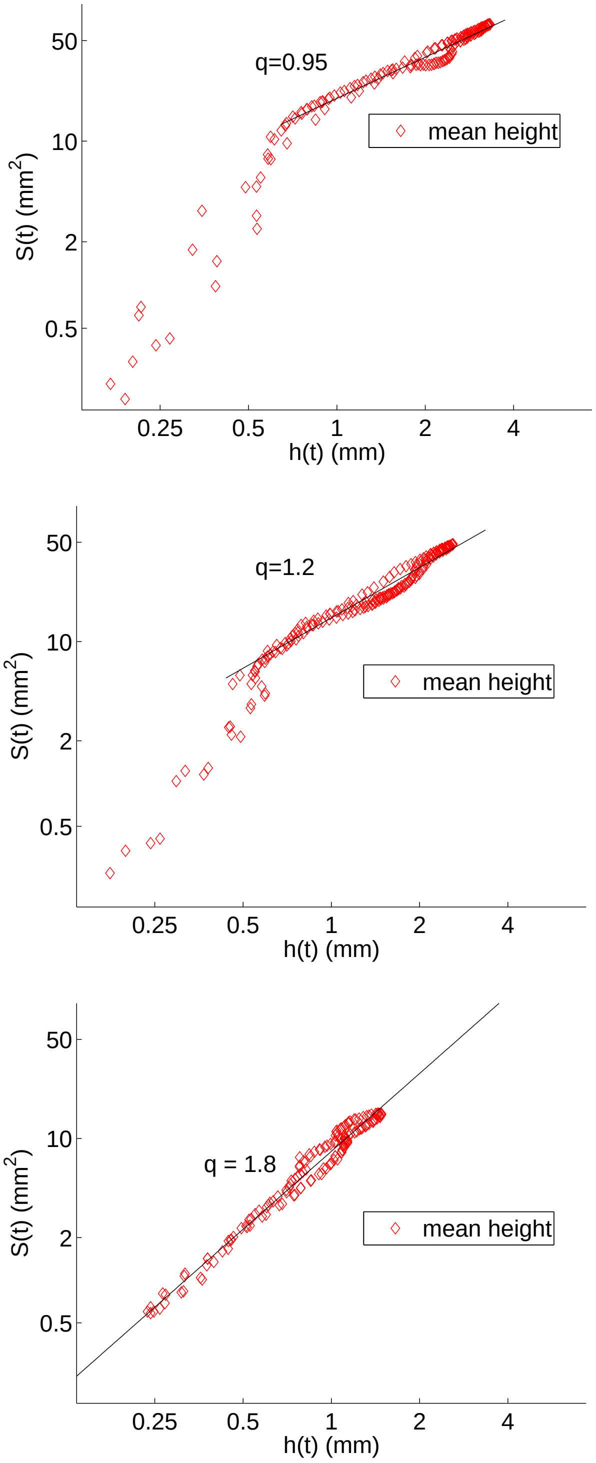


Figure 4.30: Logarithmic area-height plot showing Player A, note B$\flat_1$ dynamic levels (from top down) *ff mf p*.

table 4.2 and in appendix A.

Table 4.2: Example results - player A

Note	Dynamic	level (dB)	q
B♭$_1$	*ff*	110	0.95
B♭$_1$	*mf*	98	1.2
B♭$_1$	*p*	83	1.8
B♭$_2$	*mf*	95	1.3
B♭$_2$	*p*	86	1.7
F$_3$	*mf*	97	1.6
F$_3$	*p*	87	1.8
F$_4$	*ff*	127	1.8
F$_4$	*mf*	109	1.9(1.5-2.5)
F$_4$	*p*	100	2.4

Effect of change in dynamic level - artificial mouth

The exponent value q does not appear to vary significantly with changes in mouth pressure (and hence sound level) for the experiments carried out with the artificial mouth. Figure 4.31 shows results from one note (E3) which was sounded at various levels the minimum and maximum of which are shown. The value of the exponent is the same in each case (1.5). Table 4.3 gives the full range of results for this note and show only small variations in exponent q obtained.

Table 4.3: Example results - artificial mouth

Note	Approx dynamic	mouthpress(mbar)	level (dB)	q
E$_3$	*p*	7	85	1.5
E$_3$	*mp*	12	92	1.5
E$_3$	*mf*	14	95	1.57
E$_3$	*mf*	16	97	1.63
E$_3$	*f*	30	103	1.55

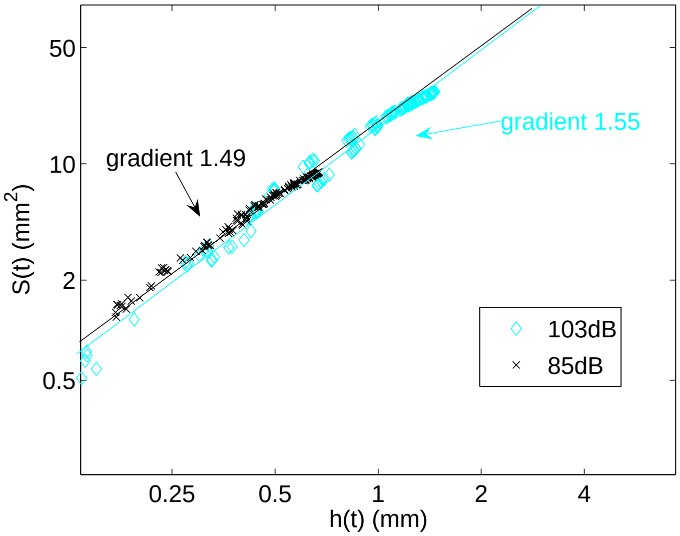


Figure 4.31: Logarithmic area-height plot artificial lips E3 at 85dB and 103 dB

Summary

It appears that for the musicians at least there is a clear relationship between the amplitude of the lip oscillation and the value of the exponent q. As the amplitude decreases, whether it is due to an increase in pitch or a decrease in sound level, there is an increase in the value of the exponent q. For the artificial lips the results are less clear. There does appear to be a similar relationship for variations in pitch, however changes in sound level do not appear to affect the exponent q. When a musician is increasing the sound level of a note they do not simply blow harder they also make changes to their embouchure. This is obviously not the case for the artificial lips where the change in sound level is made purely by a change in the mouth overpressure.

4.4.3 Variations within one cycle of oscillation

Hysteretic effects

The hysteresis evident in the area-height plots appears to be linked with asymmetry in the opening and closing parts of the cycle. Figure 4.32 (left) shows the area, height and width of the lip opening as a function of time for the note $B\flat_1$ *mf*. The opening part of the cycle appears to be much shorter than the closing part, see figure B.1 and the films described in Appendix C. The corresponding area-height plot, given in figure 4.28(a), displays significant hysteresis. By contrast there is little or no asymmetry in the cycles of oscillation for the note $F_4 mf$ shown in Figure 4.32 (right) and no hysteresis evident in the corresponding area-height plot given in figure 4.28(b).

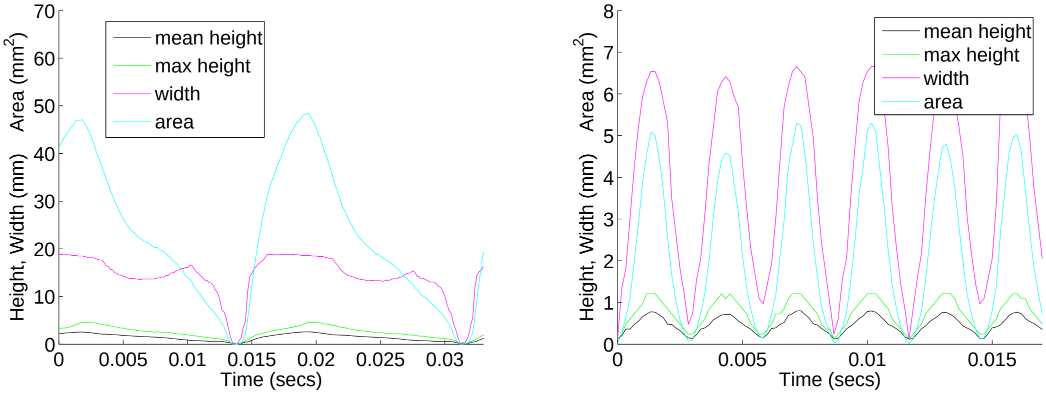


Figure 4.32: Area, height and width as a function of time, Player A, (left) note $B\flat_1$ *mf* and (right) $F_4 mf$

The amount of asymmetry in the cycles and hysteresis in the area-height plots seems to be inversely related to the value of the exponent q. This behaviour is most significant in high amplitude, low pitched notes which have the lowest q values. One of the most striking examples is that given in figure 4.33 (a) where two distinct slopes are shown. The plot of open area as a function of time given in figure 4.33 (b) is clearly asymmetrical. The lower slope corresponds to the opening part of the cycle and the upper slope the part of the cycle as the lips are closing. This suggests that the other cases of less obvious hysteresis or variations in slope may be due to distinct regions of behaviour within each cycle of oscillation.

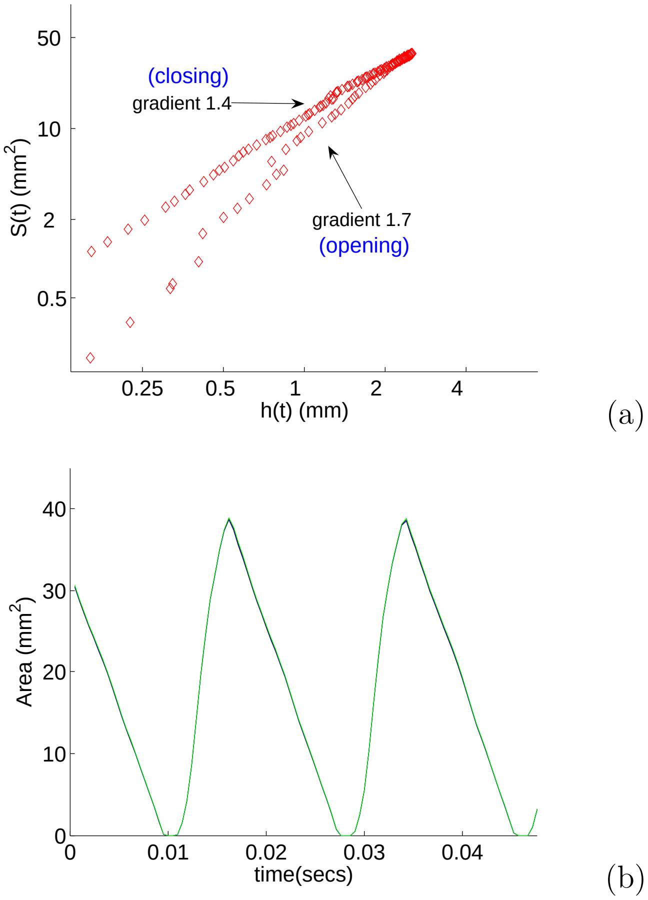


Figure 4.33: (a) Logarithmic area-height plot showing two distinct slopes and (b) lip opening area as a function of time showing asymmetry. Player M, note $\mathrm{A}_1 p$

Distinct regions of behaviour within one cycle

Section 4.4.1 introduced the idea of the importance of choosing the correct range over which to apply the linear fit. On closer inspection it can be seen that the gradient is rarely close to constant over the full range of amplitudes of opening and it may be important in some cases to split the cycle into several distinct regions of behaviour.

Figure 4.34 shows data obtained from one cycle of oscillation of the note B$\flat_1$*mf* from player S. The three data sets correspond to different parts of the cycle (opening, mid-cycle, and closing). The exponent q is close to 2 for most of the cycle, but in mid-cycle where the lips are at the maximum amplitude of opening then the exponent q is close to 1. The data is separated into three sections identified by reference to figure 4.35 which shows the opening area, height and width against time.

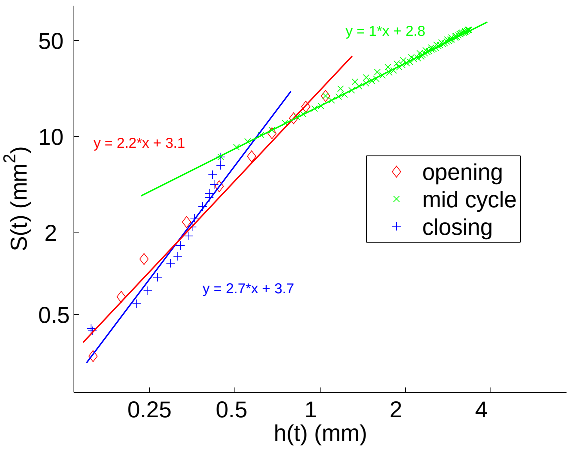


Figure 4.34: Logarithmic area-height plot showing Player S, note B$\flat_1$*mf*

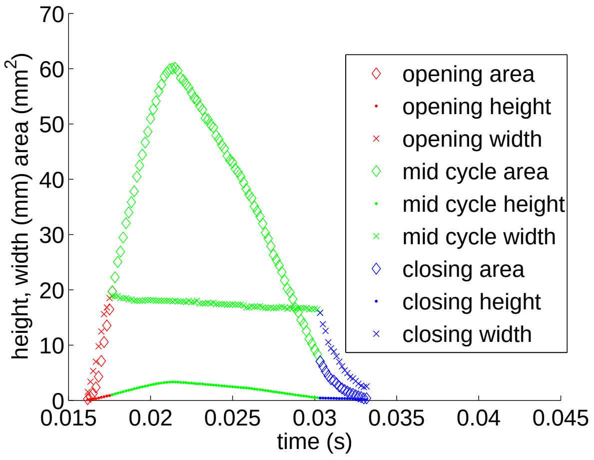


Figure 4.35: Area, mean height and width against time, Player S, note B$\flat_1$*mf*

Inspection of the corresponding area, height and width against time plot (figure 4.35) allows reference to the lip motion at these transition points. The majority of the cycle is the section shown in green, where the width is constant and the exponent q is close to 1, ie the area and height are related linearly.

Returning to the type of behaviour seen in figure 4.33, but now with reference to the variation in width it can be seen that the same regions of behaviour can be identified (see figure 4.36).

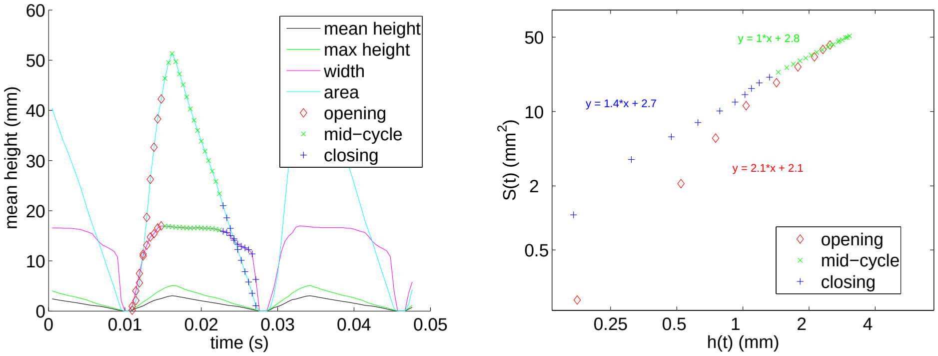


Figure 4.36: (left)Area, mean height and width against time, Player M, note $A_1 mf$ (right) Logarithmic area-height plot

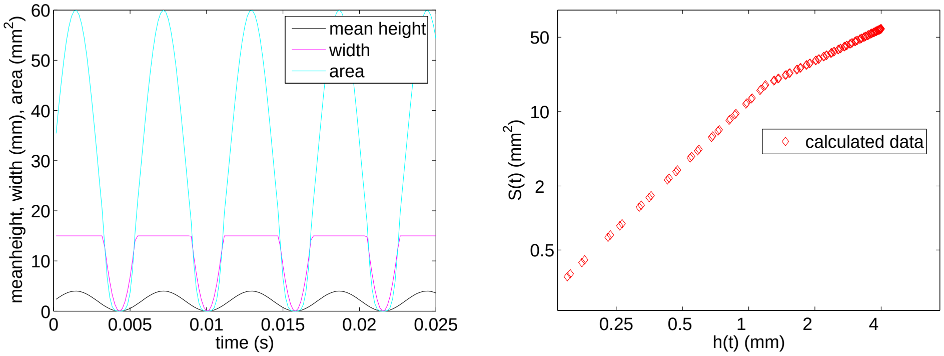


Figure 4.37: A third theoretical case, based on the simple cases presented in figure 4.22, modelling behaviour described in section 4.3.2 where the width varies sinusoidally but has an upper limit. The area data (left) is calculated using sinusoidal variations in mean height with time. The logarithmic area-height plot (right) gives a combination of the two simple cases presented in figure 4.22 namely a slope of two changing to a slope of one at high amplitudes.

Figure 4.22 presented two different theoretical cases, one linear and one quadratic, determined by the behaviour of the width of the opening as a function of time. Figure 4.37 shows a third case where as before the mean height varies sinusoidally with time and the area of the opening is calculated from the mean height multiplied by the width. In this third case behaviour described in section 4.3.2 is modelled, that is allowing the width to vary sinusoidally but with an upper limit; the logarithmic area-height plot gives a combination of the two previous cases namely a slope of two changing to a slope of one at high amplitudes. This third theoretical case seems to reproduce well behaviour seen in the experimental results such as those presented in figures 4.34 and 4.36

Figure 4.38 again shows data from one complete cycle of lip motion in this case for player TJ playing the note B$\flat_2$*mf*. The three data sets correspond to different parts of the cycle (opening, mid-cycle, and closing). The exponent q is close to 2 for most of the cycle, but in mid-cycle where the lips are at the maximum amplitude of opening then the exponent q is close to 1.

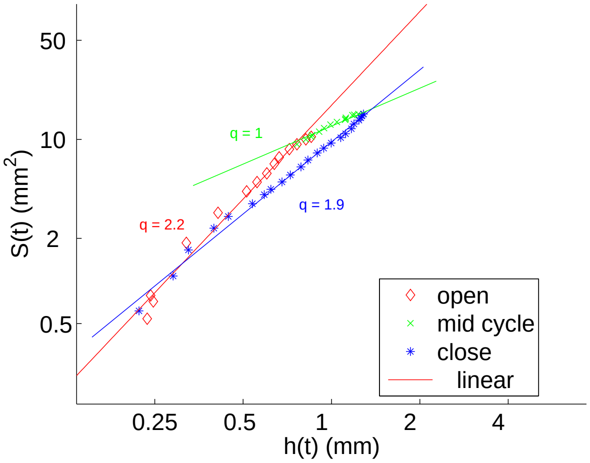


Figure 4.38: Logarithmic area-height plot showing Player TJ, note B$\flat_2$*mf*

Again inspection of the corresponding area,height and width against time plot (Figure 4.39) allows reference to the lip motion at these transition points. It can be seen that for the majority of the opening part of the cycle (shown in red) the

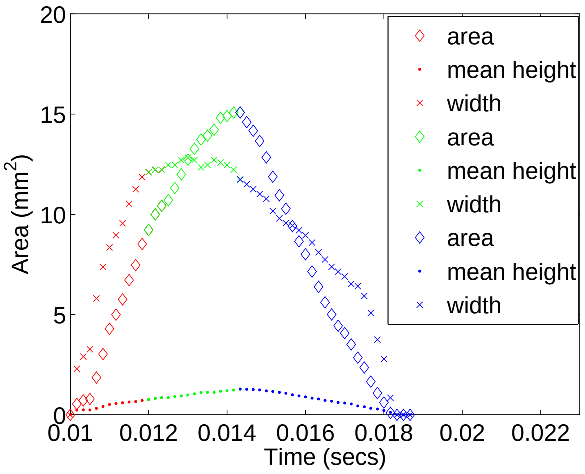


Figure 4.39: Area, mean height and width against time, Player TJ, note B♭$_2$*mf*

area and height and width increase steadily. For the small portion of motion mid-cycle (in green) the area and height are still increasing but the width is almost constant. For the remainder of the cycle (shown in blue) the width, area and height all decrease.

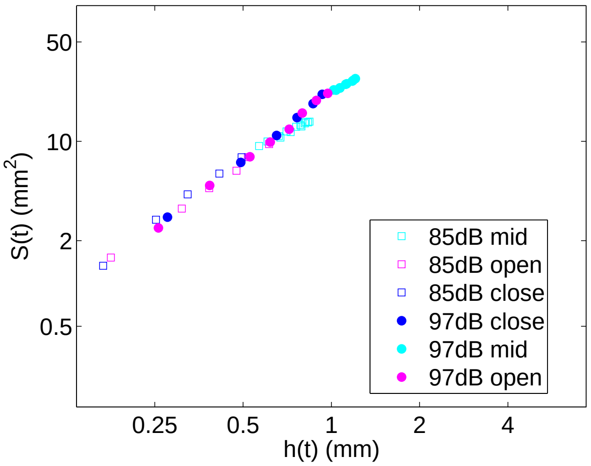


Figure 4.40: Logarithmic area-height plot for the note E$_3$ played by the artificial mouth. The mid-cycle data gives a slope of 1.1 and the opening and closing data gives a slope of 1.5 or 1.6

Similar behaviour is seen in results from the artificial mouth, but less obvious. Figure 4.40 shows data for the same note, E$_3$ played at two different sound levels.

Again distinct slopes can be identified, including a region of slope around 1 in the mid-cycle; the opening and closing regions give a slope of approximately 1.5.

4.4.4 Summary

One of the main aims of this work was to provide physical evidence to guide simulations of lip behaviour. To this end a more detailed description of the form of the relationship between the the lip opening area and height has been developed. A general area-height function $S(t) \propto h(t)^q$ has been assumed and values obtained for the exponent q. Results have been obtained using both the artificial mouth and real musicians which confirm and extend the findings of earlier initial experiments[82]. A relationship between the amplitude of the lip oscillation and the value of the exponent q has been shown to exist. The results from musicians show that as the amplitude decreases, whether it is due to an increase in pitch or a decrease in sound level, there is an increase in the value of the exponent q. The results from the artificial lips show a similar relationship for variations in pitch, however changes in sound level do not appear to affect the exponent q. Results have shown that a single value of the exponent q is not sufficient to represent the full detail of the behaviour, but that distinct regions within a cycle of oscillation have been identified.

4.5 Extremely loud playing - the ‘brassy’ sound

4.5.1 Background and motivation

The harmonic content of the sound from a brass instrument at quiet and moderate playing levels can be explained by the primary nonlinearity of the lip-reed which is the origin of the non-sinusoidal waveforms of the pressure and flow measured in the mouthpiece [11, 37, 42]. When playing brass instruments at the loudest dynamic levels there is a distinct change in timbre to a ‘brassy’ sound characterised by a significant increase in the levels of the higher harmonics. Nonlinear progression of the wavefront along the bore of the instrument results in a transfer of energy from low to high harmonics [42] and is generally accepted to be the origin of this ‘brassy’ sound [21]. It has been suggested [100][65][45] that the lip opening saturates at high amplitudes due to the constraining effect of the mouthpiece rim. The aim of this section is to investigate the behaviour of the time varying movement of the lip opening at the loudest dynamic levels.

4.5.2 Method

The experimental setup and image analysis procedure was as described in section 4.2. The player was asked to sound several notes in pairs of the same pitch but at different dynamic levels: one clearly brassy to the player’s ear, the other non-brassy (and typically somewhat quieter). The radiated sound was recorded at a distance of one bell radius using an Audio-Technica ATM33a condenser cardioid microphone and a Marantz Professional PMD671 hard disk recorder. To measure the pressure in the mouthpiece a PCB microphone was inserted in a half inch hole in the side of the transparent mouthpiece cup, as shown in figure 4.41.

Figure 4.41: Transparent mouthpiece with PCB microphone.

Figure 4.42 gives example waveforms for the radiated sound of a pair of recordings; both were obtained by asking the player to sound the note F_3. Figure 4.43 gives the frequency spectra for these notes. The waveform and spectrum of the radiated sounds show clear differences between brassy and non-brassy playing. The radiated sound for non-brassy playing is far less dominated by the higher harmonics, with no significant peaks above 5kHz. In contrast, the brassy note shows only an 30dB drop-off over the same range.

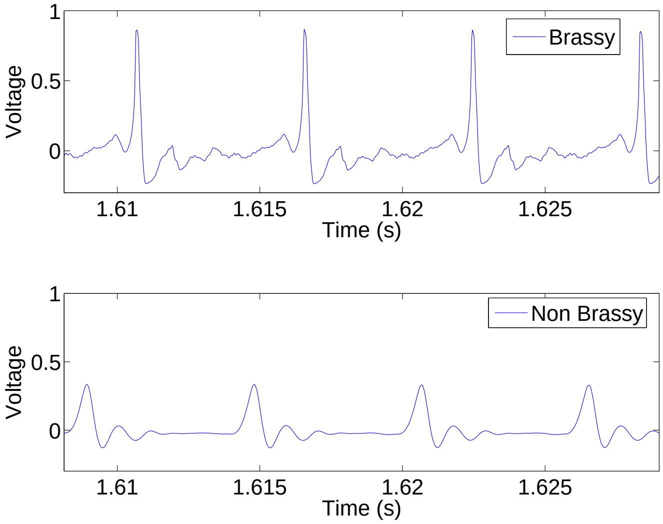


Figure 4.42: Radiated sound waveforms for brassy and non-brassy playing of the note F_3.

Figure 4.44 shows the radiated sound waveform and corresponding mouthpiece pressure waveforms for the note D_4 played at three different dynamic levels. The louder two levels (labelled *fff* and *f*) are the brassy and non-brassy notes investigated in this section. The increasing nonlinearity in the mouthpiece pressure waveforms can be clearly seen. The change in the waveform of the radiated sound from *f* to *fff* level is dramatic with the development of an obvious sudden pressure increase as described in [55].

Figure 4.45 shows normalised waveforms for the lip opening area for the notes

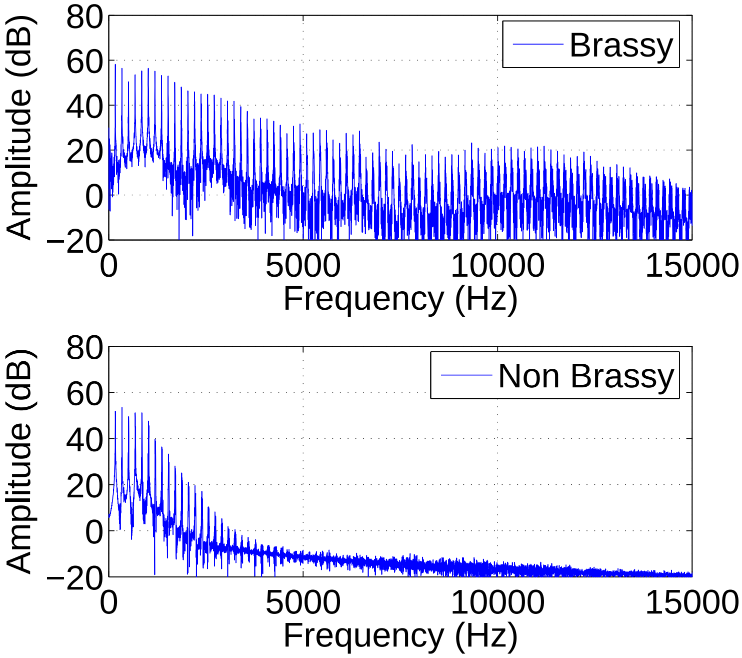


Figure 4.43: Frequency spectra of radiated sound for brassy and non-brassy playing of the note F$_3$.

B$\flat_1$, B$\flat_2$, F$_3$ and D$_4$. Small differences in behaviour can be seen, notably a slight increase in asymmetry in the louder notes with the lips taking longer to close than to open. This is consistent with observations in previous studies [30]. The similarity in the form of the rising edge of the curves, particularly for the notes B$\flat_2$ and F$_3$, is quite striking.

The un-normalised area waveforms are given in figure 4.46. Comparing brassy with non-brassy notes of the same pitch reveals significant differences in the amplitude and rate of lip opening. For the brassy notes the lips generally open much more rapidly; enabling the development of a maximum opening area that is approximately three times larger than the equivalent non-brassy notes.

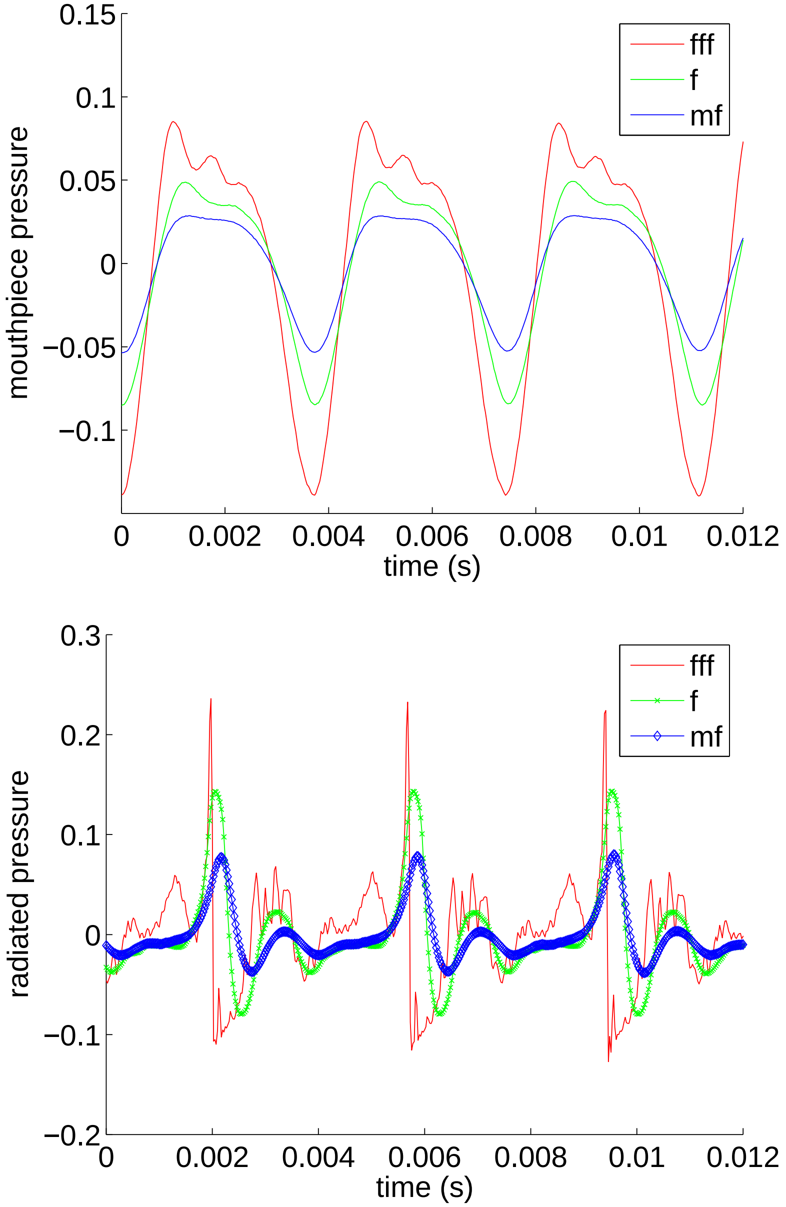


Figure 4.44: Radiated sound (bottom) and mouthpiece pressure (top) for note D_4 played at three different dynamic levels

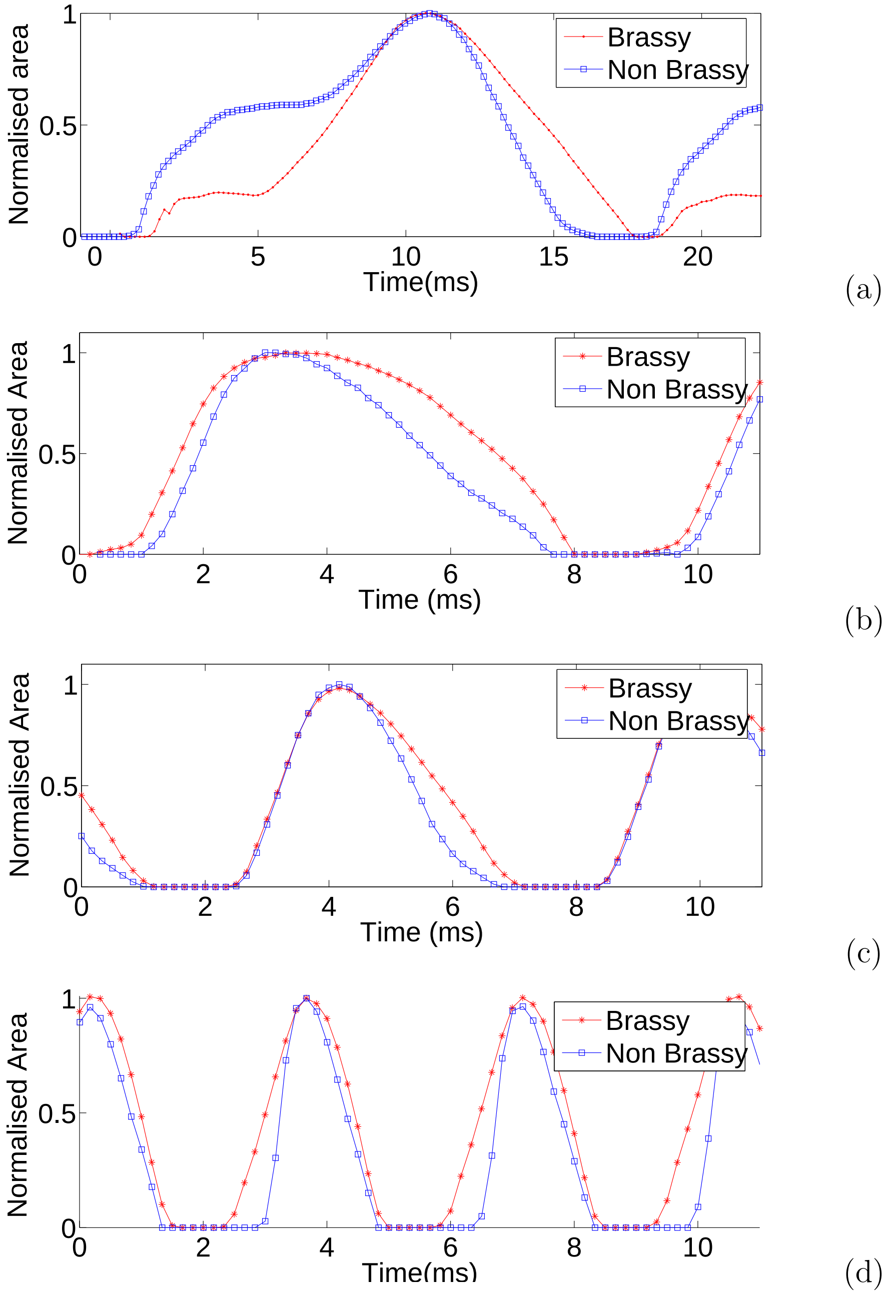


Figure 4.45: Normalised lip opening area for notes (a) B♭$_1$, (b) B♭$_2$, (c) F$_3$, and (d) D$_4$.

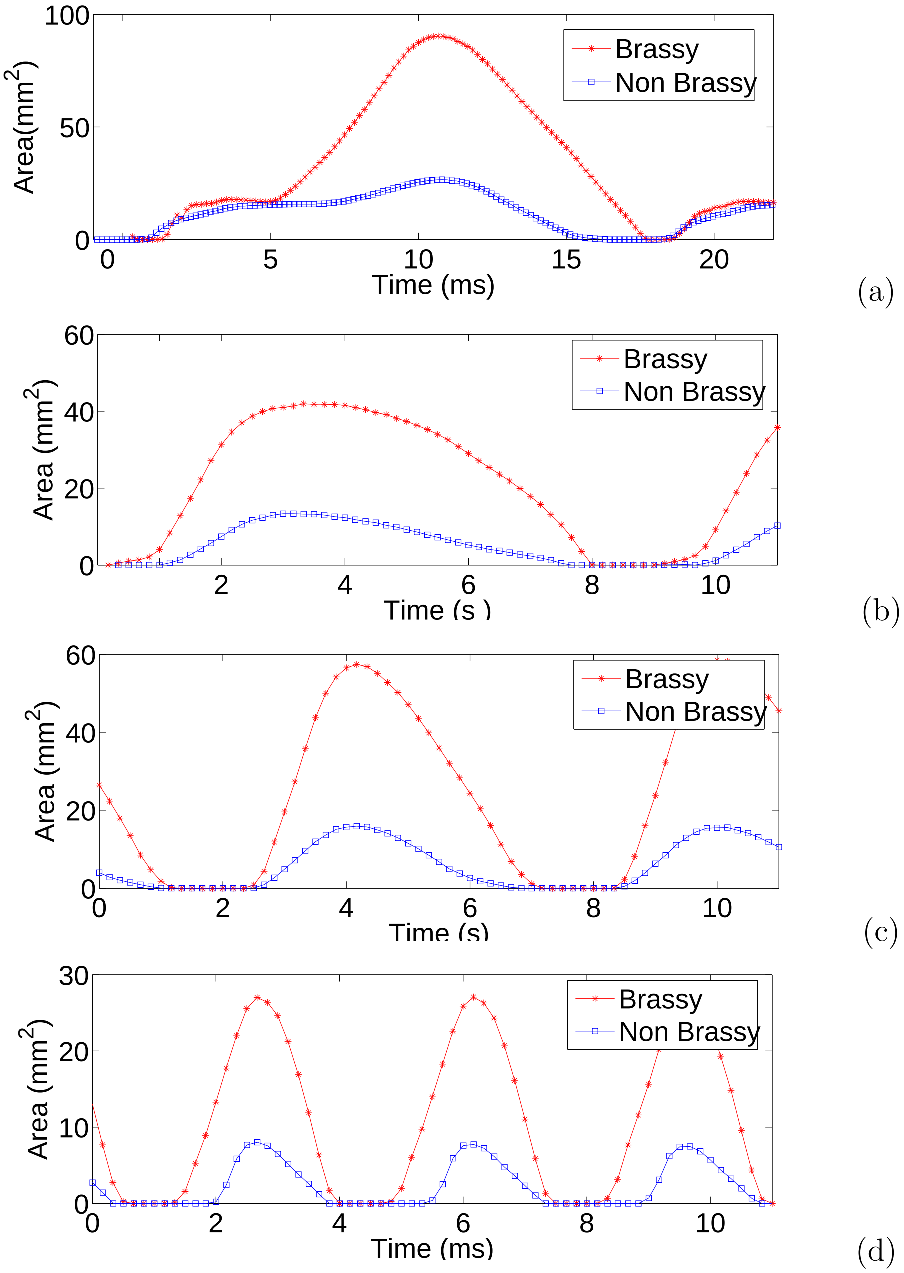


Figure 4.46: Lip opening area for notes (a) B♭$_1$, (b) B♭$_2$, (c) F$_3$, and (d) D$_4$.

4.5.3 The area-height function

Figure 4.47 is a logarithmic plot of area $S(t)$ against height $h(t)$ for the note B$\flat_1$ played extremely loudly and also at a more modest sound level. The value for the exponent q in the relationship $S(t) \propto h(t)^q$ is found from the gradient of a straight line fit as in section 4.4. Qualitative comparison of the results for extremely loud playing in figure 4.47 with those at more modest sound levels reveals no apparent difference in the behaviour. The values of the exponent q are 1.3 for the majority of the cycle and 3.1 for the low amplitude data; these values are consistent with those presented in section 4.4.

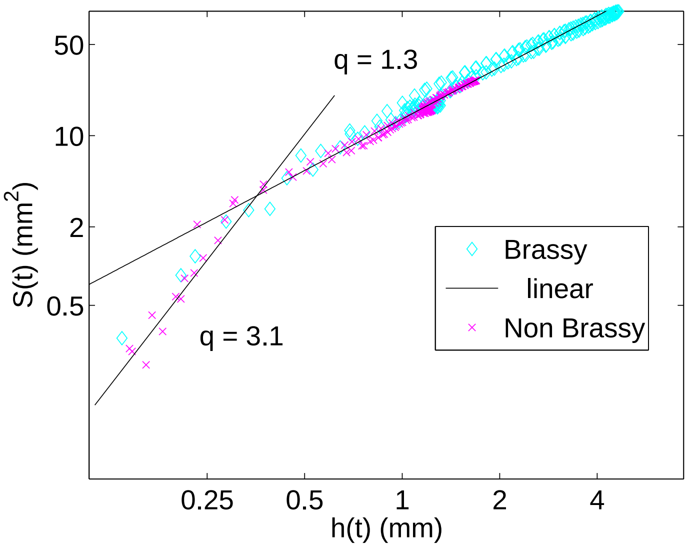


Figure 4.47: Logarithmic area-height plot for the brassy non-brassy playing of the note B$\flat_1$.

4.5.4 Discussion

The plots of normalised area against time show that under some circumstances there are small differences in open area waveform between brassy and non-brassy notes played at the same frequency. In general it takes slightly longer for the lips to close for the brassy notes, but there is no evidence of a pronounced 'flattening' of the curve at maximum open area. Although the curve for the trombone B$\flat_2$ does show a slight flattening and the final stage of the lip closing is a little more abrupt for this measurement, these differences are too small to significantly affect the radiated spectrum.

The most significant difference observed is in the amplitude and rate of change of lip opening area. This marked difference in the opening behaviour of the lips when playing fortissimo results in a rapid rise in mouthpiece pressure. It is this rapid and large rise in mouthpiece pressure which is necessary for shock wave formation, as described in [55].

4.6 Conclusions

A qualitative and quantitative comparison of the time variance of the area, height and width of lip opening of real and artificial lips was given in section 4.3. Results show an increase in amplitude of lip motion with increasing sound level but decreases with increasing frequency, with small magnitude variations between players and between different embouchures on the artificial mouth. The height and area of the lip opening vary smoothly over the course of each cycle of oscillation. The width of the opening displays regions of almost constant value at maximum opening, particularly for low pitched loud notes, and less so with increasing pitch or reducing sound level. Although some differences have been identified between the behaviour of the artificial lips and that of the lips of musicians, the general features of behaviour are reproduced by the artificial mouth.

Section 4.4 explored the definition of a function relating area and height useful in modelling. A general area-height function $S(t) \propto h(t)^q$ has been assumed and values obtained for the exponent q, using both the artificial mouth and real musicians. The results from musicians show that as the amplitude of the lip oscillation decreases, whether it is due to an increase in pitch or a decrease in sound level, there is an increase in the value of the exponent q. The results from the artificial lips show a similar relationship for variations in pitch, however changes in sound level do not appear to affect the exponent q. It has been shown that a single value of the exponent q is not sufficient to represent the full detail of the behaviour, but that distinct regions within a cycle of oscillation have been identified. Gilbert *et al* [51] have presented a study of a harmonic balance model of a trumpet, using data reported here which shows noticeable timbral differences between sounds produced with the exponents $q = 1$ and $q = 1.5$. Future models which incorporate a form of the area height relationship which varies during each cycle may yield interesting results.

The final section of this chapter looked at the special case of extremely loud playing. Results suggest that during extremely loud playing the lip motion is qualitatively similar to quieter notes and that small changes in the lip motion are not responsible for the dramatic change in timbre of the radiated sound.

Chapter 5

Transient behaviour

Up until this point we have looked only at the steady-state behaviour of the brass player's lips. It is clear that this steady state does not come about instantaneously, but after some time during which the various parts of the system begin to cooperate and eventually settle on a stable behaviour which sustains itself. It is well established in many studies (see for example [15, 86, 62]) that the beginning and ends of a note, the transients, are of extreme importance in the identification of characteristics of a note such as the timbre. Indeed reliable identification of instruments is often not possible when the transient sections of the note have been removed from a recording.

One characteristic which may distinguish a good instrument from a bad one is the ease and manner with which a player is able to start the note. There are two main areas of instrument design to consider in the development of the note [14, 13]. Firstly the same characteristics which define an instrument's ability to sustain a note, namely a requirement for harmonically related resonances (as described in section 2.4.3) also affect the initial development of the note. Secondly there is the length of time taken for the initial disturbance caused by the movement of the lips to travel along the air column of the instrument, be reflected at the bell, and to the return to the lips. Before this time has elapsed the lips are operating without any information about the instrument and its resonances. It is this factor which is considered here with the aim of developing a technique which could also be applied to studying other variables which affect the transients.

5.1 Experimental procedure

In order to analyse the transient motion of the brass player's lips, an experiment was designed to synchronise audio recordings with high speed camera footage. A schematic diagram and photograph of the experimental process are shown in figures 5.1 and 5.2 respectively.

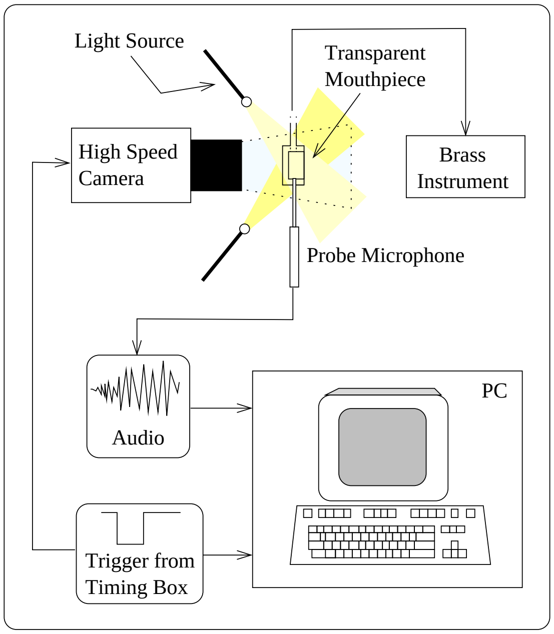


Figure 5.1: Schematic of the experimental equipment used for measuring the motion of a horn player's lips.

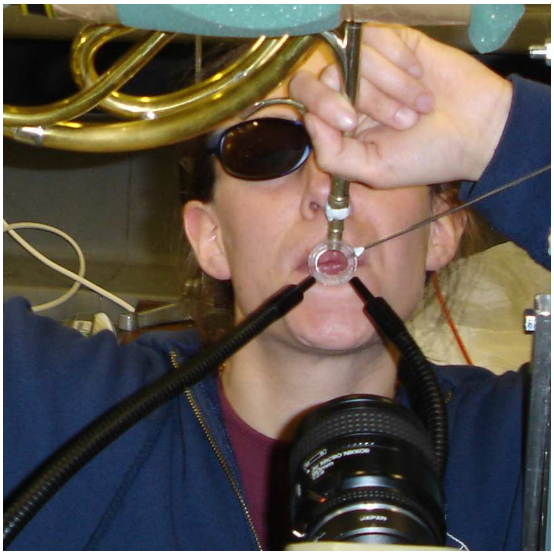


Figure 5.2: Photograph of the experimental equipment used for measuring the motion of a horn player's lips.

5.1.1 The instrument

The instrument chosen to be used for these experiments was a medium bore Paxman model 40, B♭/F-alto double descant horn. This instrument allowed for tests to be carried out using tube lengths of approximately 1.8m and 3.6m by operating different valve combinations.

The mouthpiece design is similar to that used for the experiments with the trombone (described in section 4.2.1). As with the trombone mouthpiece the cup is machined from perspex, and the front is made from thin optical glass to provide a window through which the lips can be visualised. It is important to reproduce closely the design of the mouthpiece in order to preserve the playing characteristics[14, 77]. To this end the shank (including throat and back bore) has been taken from a Paxman 4C mouthpiece, and the cup volume and rim dimensions are also based on this mouthpiece.

Previous studies[103] have noted that the embouchure of a french horn player normally makes use of a significantly higher proportion of upper lips than lower and that the upper lips can be seen to protrude some way into the mouthpiece. This is behaviour which is seen in some players of other brass instruments, and is most significant when the player is sounding higher modes of the instrument, but it is particularly common in horn players. As remarked in section 4.2.1 visualising the opening of this type of embouchure can present a greater challenge. The mouthpiece was designed with this in mind and therefore the window at the front of the mouthpiece is angled so as to provide a greater depth for the upper lip than the lower lip. A photograph of the mouthpiece and diagram of the design are shown in Figure 5.3 (provided by Chick [28]).

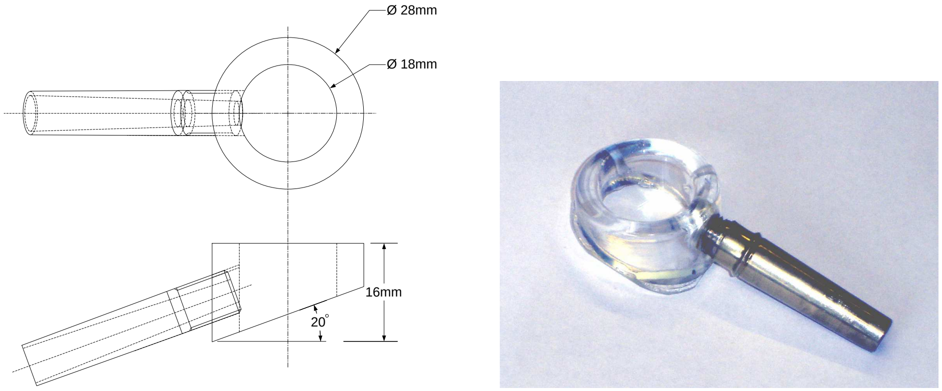


Figure 5.3: Schematic and photograph of the experimental mouthpiece.

The experiments have been carried out using two different lengths of tubes on the same horn. Both tube lengths were used to record notes F_2, F_3, F_4, and C_5 at nominally similar sound levels *forte*. The player was asked to produce as clean an attack as possible using the tongue (rather than a gradual crescendo). The experiments were repeated with the same equipment with two different players in order to identify common patterns in the motion of the lips.

5.1.2 Data acquisition

To measure the mouthpiece pressure a Brüel and Kjær 1/2" microphone was used with a 230mm long 2mm diameter probe inserted in a 2mm hole in the side of the mouthpiece. The entrance section of the probe was packed with metallic damping wool to reduce the pressure levels to within the range of the diaphragm sensitivity and also to give a more flat response. There is still some clipping evident at high amplitudes however, but as the aim of this work is to investigate the very earliest portion of the note the clipping at high amplitudes it is not a concern. The calibration curve for this probe is given in figure 5.4. As can be seen, the amplitude of the signal is reduced by between 14dB and 16dB over the range of the notes considered. The exact form of the pressure signal is not under investigation here so it was considered sufficient to apply the phase calibration appropriate to the fundamental of each note played. For example the note F_3 has a fundamental at 174Hz and therefore the calibration for this frequency is applied to this note. These phase corrections, equivalent to a delay of approximately 0.0009 seconds, were applied to the pressure signals in the post-processing.

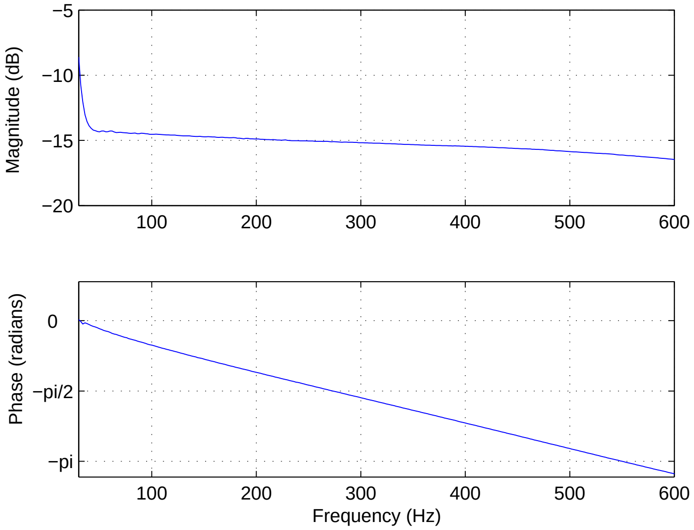


Figure 5.4: Calibration curve for the long probe.

The image capture setup and procedure were based on those described in section 4.2.1. The image size chosen for these experiments was 256 by 64 pixels as this allowed the maximum number of pixels in the correct aspect ratio for the lip opening. It was necessary to use a reasonably long capture time of 3.6 secs to ensure the capture of the transient portion of the note. The maximum frame rate available for this image size and capture time of 5000 frames per second was used.

Even with the angled mouthpiece viewing window there was difficulty in visualising part or all of the opening between the lips due to ‘overhang’ of the top lip. This was particularly a problem with high notes, where the amplitude of motion is small. This difficulty could partly be overcome by adjusting the camera angle, but in practice this proved difficult. As this study was interested in the changing motion of the lips and not the exact dimensions of the open area, the problem has not affected the results except in limiting the range of the notes which could be studied, with C_5 being the highest that it was practical to film.

The camera was triggered using an external Berkeley Nucleonics Corporation Model 500 pulse generator, the signal from which was recorded simultaneously with the pressure signal from the probe microphone using the Brüel and Kjær PULSE system. This then allowed the identification of the point in the audio time axis which corresponded to the first captured image, and hence the synchronisation of the two data sets.

5.1.3 Analysis procedure

The high speed digital films were edited to produce a series of images which show the transient, the frame numbers corresponding to part of the time axis of the audio data. The individual frames were also cropped to show just the lip opening, in order to reduce the data size for analysis. The analysis software described in section 4.2.2 was used to assign a threshold grey level which distinguished the lip opening from the remainder of the image, as demonstrated in Figure 5.5. The number of pixels in the open area were then counted for each image and this area plotted against time.

The synchronised mouthpiece pressure data has been normalised and added to the plots of open area in order to allow comparison of the two synchronised data sets (open area and mouthpiece pressure).

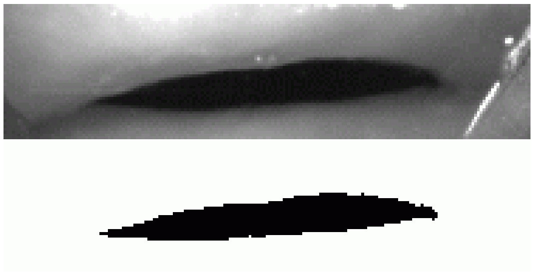


Figure 5.5: One image of lip opening and the corresponding ‘thresholded’ image.

5.2 Results

The reproducibility of results relies on the skill of the player in producing an equally ‘good’ attack with each measurement. There is therefore some degree of variability between nominally similar measurements. For this reason the high speed digital videos show significant variation if all measurements are considered. The skilled players were however usually a good judge of the quality of their attack and were therefore able to advise on which data should be discarded and the measurements repeated. Even with this selection procedure there is still some inevitable variability in results; nonetheless, some interesting patterns can be identified. Results from only one player are presented, though similar behaviour was observed for both subjects.

5.2.1 Input impulse response measurements

One obvious timescale over which to consider the transient behaviour is the time for the initial pressure disturbance to travel along the instrument, be reflected at the open end and return to the lips. It is only after this time that the lips receive information about the instrument resonance to which their behaviour must be coupled [14, 13]. This round trip time can be obtained from input impulse response measurements of the instrument. Figure 5.6 was obtained using apparatus in the School of Physics developed by Kemp [58]. The round trip time given for the low F horn (3.6m) is approximately 22ms. A similar curve for the F-alto horn (1.8m) gives a round trip time of approximately 11ms. It should be noted that the round trip time is determined by the group velocity and so is not necessarily directly related to the periodicity of any of the modes of vibration of the air column.

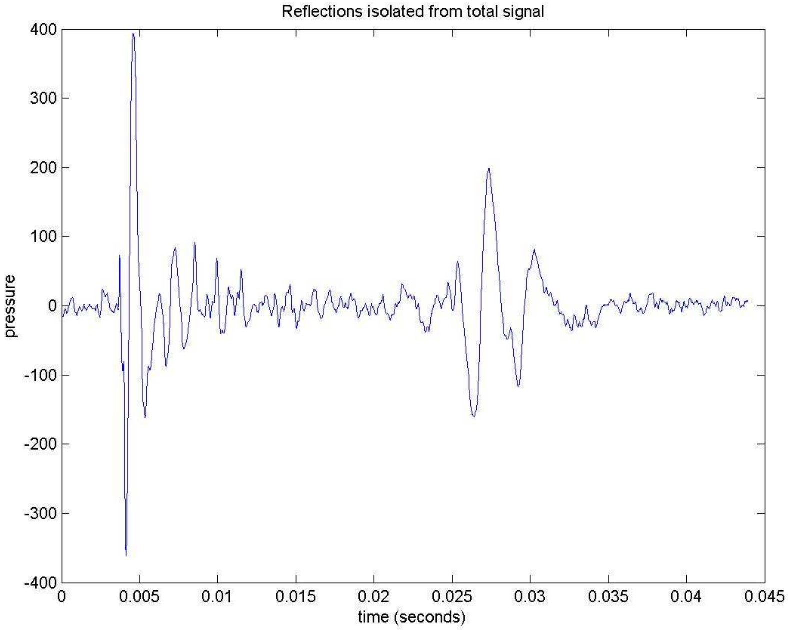


Figure 5.6: Input impulse response curve for the 3.6m horn showing a round trip time of approximately 22ms. Graph provided by Newton[75].

5.2.2 Amplitude

Figure 5.7 shows a graph of lip open area and normalised mouthpiece pressure for the first 14 cycles of the note F_4 played on the 3.6m horn. The corresponding series of lips images (rotated by 90°) showing the maximum opening for each of first 14 cycles are also presented. It can be seen that the amplitudes of the mouthpiece pressure oscillations remain almost constant over approximately the first 20ms of the note, whilst there is a gradual reduction in the mean pressure. The reason for this reduction in mean pressure is not clear. After this time there is an obvious increase in both the mean pressure and the amplitude of oscillation. Evidence is also present of a change in the rate of increase of the open area at the same time; this can be observed qualitatively when viewing the corresponding

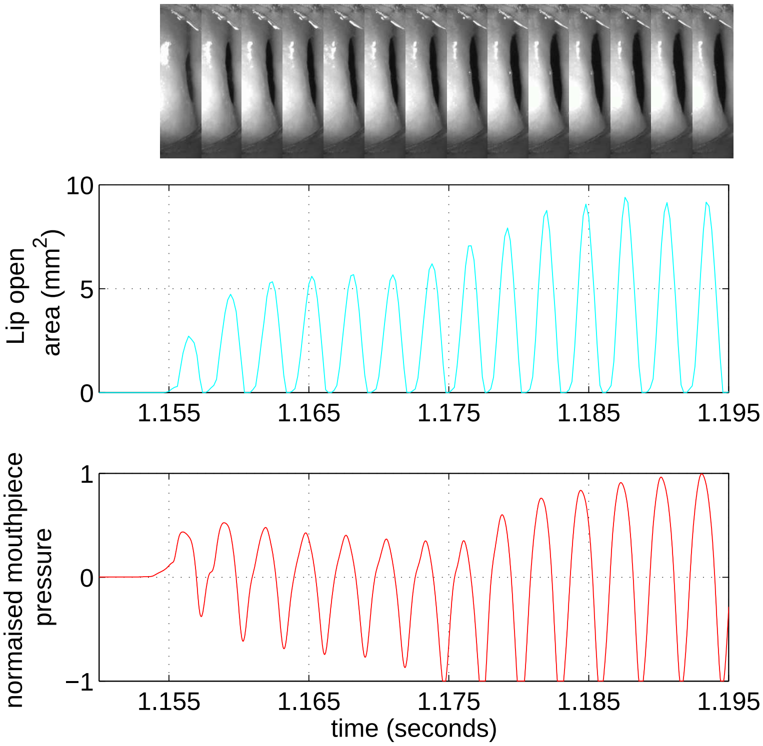


Figure 5.7: A series of lips images (rotated by 90°) showing the maximum opening for each of the first 14 cycles of the note F_4 played on the 3.6m horn, and the corresponding graph of open area and mouthpiece pressure.

series of images.

The same behaviour can be seen in figure 5.8 which shows a series of plots of open area and synchronised mouthpiece pressure for the attack transients for the full range of notes investigated on the 3.6m horn.

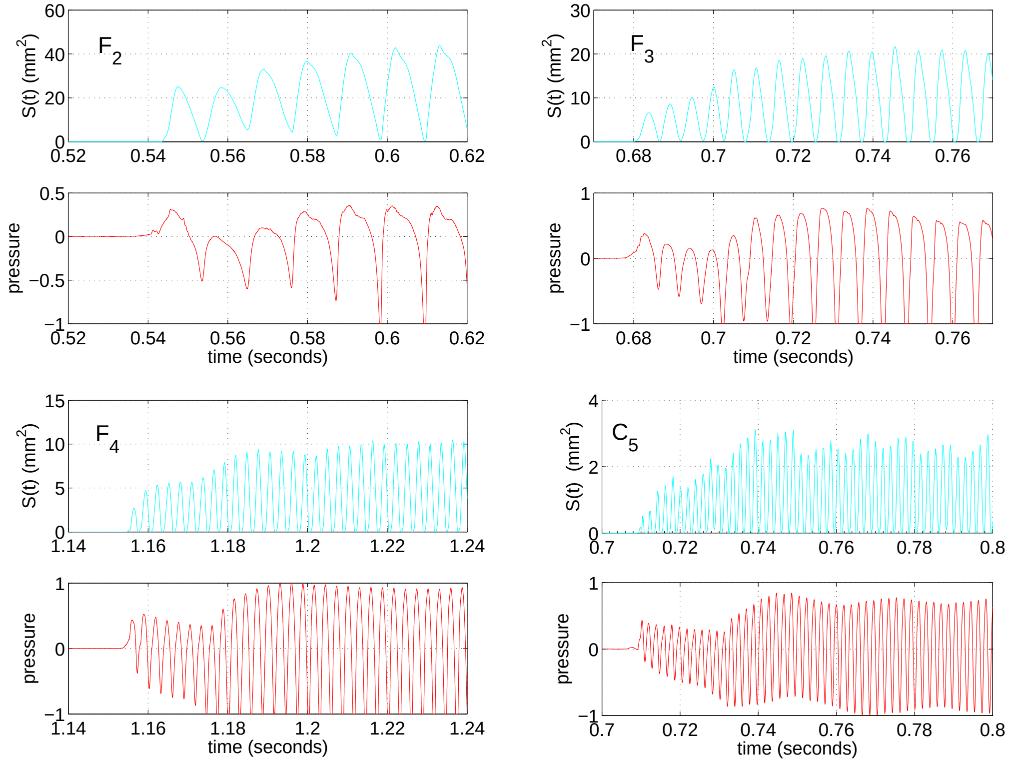


Figure 5.8: Lip opening area, S(t), and normalised mouthpiece pressure transients for the 3.6m horn.

Figure 5.9 shows the equivalent series of plots of open area and synchronised mouthpiece pressure for the attack transients of the same four notes played on the 1.8m horn. Similar behaviour is observed over a shorter timescale, with changes evident at approximately 10ms. In both cases (3.6m and 1.8m horns) the observed changes in behaviour occur at a time which corresponds well with the measured round trip time for each instrument.

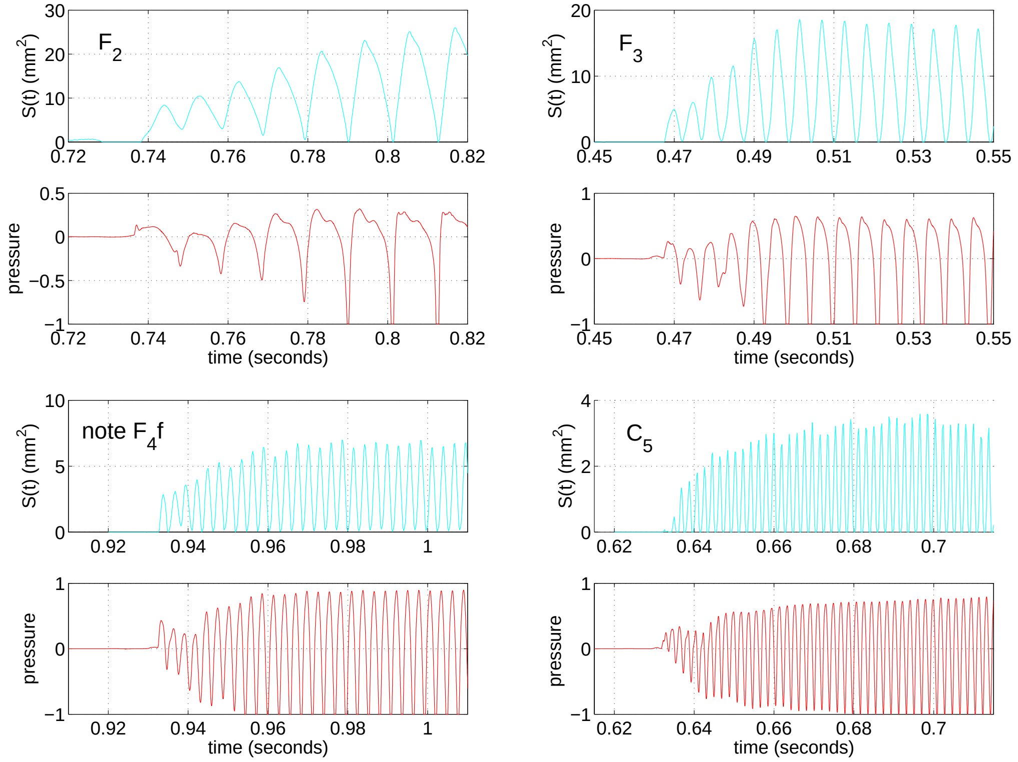


Figure 5.9: Lip opening area, S(t), and normalised mouthpiece pressure transients for the 1.8m horn.

5.2.3 Frequency

A peak detection program was used to calculate the time between consecutive pressure maxima for the mouthpiece pressure data. This was then used to calculate the equivalent frequency of the note at that time. Figure 5.10 shows plots of calculated frequency against time for the first 0.18 seconds of each of the same four notes, played on both the 3.6m and 1.8m horns, given in figures 5.8 and 5.9. The data for the long horn is given in blue and that for the short horn is given in red. It can be seen that, in general, the frequency settles more quickly for the notes played on the short horn (approximately 40ms) than those played on the long horn (approximately 80ms), but this is most noticeable for the note F_3.

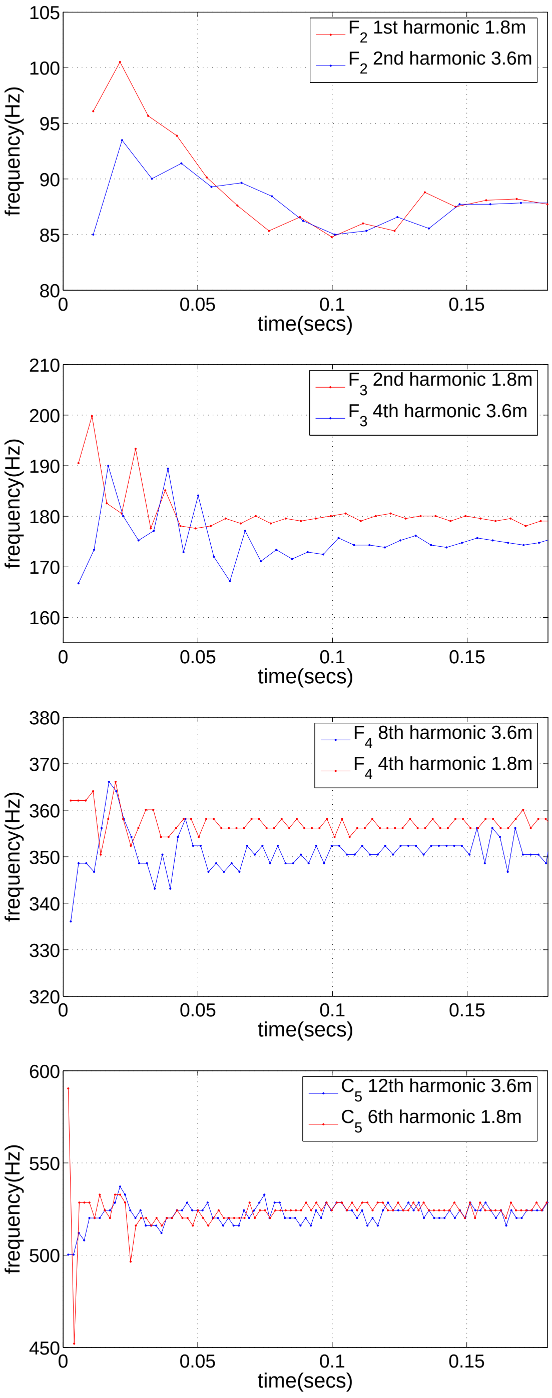


Figure 5.10: Plots of frequency ‘settling’ from mouthpiece pressures shown in Figures 5.8 and 5.9.

5.3 Conclusions and future work

In this chapter, the transient behaviour in the motion of the brass player's lips has been studied and the techniques used have been shown to be useful in relating the motion of the player's lips to the transient in the mouthpiece pressure waveform. The techniques developed provide additional information about real behaviour, both in the physical motion of the brass player's lips and the sound produced. This may be of use in providing information to aid the process of refining brass instrument physical models. This work has focused on the effect of length of horn on the nature of the transient; there are of course several other important factors, including the degree to which the mode frequencies approach a harmonic relationship and the presence of discontinuities in the bore which produce additional reflections of the initial pressure disturbance [14].

It is anticipated that future work would involve further experiments carried out on a wider range of brass instruments and players in order to confirm the initial conclusions drawn from the analysis. The development of a realistic tongue mechanism for the artificial mouth [82] would allow similar investigations without the variability inherent in human playing. This could allow consistent testing of a range of instruments looking at for example, the ease of starting a note. A further development could also focus on relating the initial playing frequency to the amplitude changes, looking for evidence of a cleaner attack if the player is able to accurately initiate lip vibration at a frequency close to the desired playing frequency.

The observed changes in the envelope of the mouthpiece pressure occur on a timescale which is significant when compared with the overall transient length. It is therefore expected that these differences would be perceptible to the human ear. Listening tests on recorded radiated sounds, and/or synthesised versions of sounds incorporating the measured effects, would be an interesting extension of this work.

Chapter 6

Example experiments using the artificial mouth for comparative studies of historic instruments

Various previous studies have made use of objective techniques such as bore profiling and input impedance measurements; see for example:Backus[8], Myers[69], Pratt[80, 81], Causse[26]. In addition various researchers have made use of subjective listening studies for the comparison of instruments; for example Pratt[79], Carral[25]and Bertsch used blind testing by musicians. Petiot[76] has developed a new version of the artificial mouth for use as a 'test bench' for comparative analysis of brass wind instruments. Poirson[78] used a variable depth mouthpiece to investigate the influence on the brightness of trumpet tones. This study used both objective measurements and subjective listening tests and concluded that the artificial mouth was an important tool in such tests. The work in this chapter aims to explore the use of the artificial mouth as a tool for use in investigation and comparison of historic instruments.

6.1 Background and motivation

One of the major benefits of using an artificial mouth in instrument studies, instead of a musician, is the increased level of control over the various parameters which define the playing embouchure as well as the flow and pressure at the mouth. This greater control and stability allows separate investigation of the role of various parameters, for example supply pressure, in determining the note produced. By using a stable embouchure it is possible to perform more reliable comparative studies of instruments (see chapter 3).

6.2 The ophicleide and the saxhorn

6.2.1 Motivation and aims

The ophicleide is a keyed bugle with tone-holes covered by key-operated pads. Invented in 1817, it was popular until the development of the valved bass saxhorn (the early euphonium) in the 1840s. The aim of this series of experiments is to make a comparison of the playing behaviour of these two types of instrument in order to provide acoustical evidence which may help explain the decline in popularity of the ophicleide in favour of its valved cousin the saxhorn.

6.2.2 Instruments

The instruments and mouthpiece were provided by the Edinburgh University Collection of Historic Musical Instruments (EUCHMI). Two pairs of instruments were chosen for comparison. The first pair of instruments studied are an ophicleide in B♭ (EUCHMI 2157) and a bass saxhorn in B♭ (EUCHMI 4273) using the same 19th century Higham mouthpiece (EUCHMI 2158). The second pair are an ophicleide in C (EUCHMI 4287) and a Saxhorn basse in C with tuning-slide for B♭(EUCHMI 3812).

Figure 6.1: (left) An ophicleide in C (EUCHMI 4287) and (right) a Saxhorn basse in C with tuning-slide for B♭(EUCHMI 3812).

6.2.3 Notes played

The bass saxhorn in B♭ (EUCHMI 4273) and the Saxhorn basse in C with tuning-slide for B♭(EUCHMI 3812) were sounded with either no valves operated (referred to as V0) or the 4th valve operated (V4). In each case the note produced was F_3 (in the middle of the instrument's normal compass) as, respectively, the 3rd mode and 4th mode. The ophicleide in B♭ (EUCHMI 2157) was sounded with fingerings for $B\flat_1$, F_2 with venting (opening the $B\flat_1$ and C_2 keys), and F_2 without venting. Again in each case the note produced was F_3 (in the middle of the instrument's normal compass). Similarly the ophicleide in C (EUCHMI 4287) was sounded with fingerings for C_2, G_2 with venting, and G_2 without venting. With no keys operated (all holes covered except the one nearest the bell) the nominal playable notes on this instrument are the harmonics series of C_2 (C_2, C_3, G_3, C_4, ...). However as it is a low pitched ophicleide, probably built for A_4 = 430Hz, the note sounded was an $F_3^\sharp$.

6.2.4 Data acquisition

The mouth pressure was measured using a Digitron 2001P manometer with a probe located in the mouth cavity. The radiated sound was recorded using a Brüel and Kjær (B&K) $\frac{1}{2}''$ microphone and the B&K PULSE system, which acts as an amplifier for the B&K microphones and provides data acquisition and analysis tools (see section 3.3.1). The frequency spectra were then calculated and displayed in Matlab. As measurements were carried out in a laboratory and not an anechoic chamber the microphone was positioned on the axis of the instrument bell at a distance equal to the radius of the bell so as to minimise the influence of variations in room acoustics [14]. The sound level was measured at the same position (on the axis of the bell at a distance of one bell radius) using a CEL-254 digital impulse sound level meter.

6.2.5 Method

For each instrument fingering pattern or valve combination the following procedure was observed: Firstly, the flow from the air supply was increased by gradually opening the flow valve. This caused a gradual increase in the overpressure in mouth until the threshold for playing is reached. After the playing threshold had been reached, the flow was gradually increased causing the instrument to be sounded at different levels. At each stage the playing frequency was noted (using the real-time spectral analysis available with the PULSE system). The mouth pressure and sound level were also noted. For each pair of instruments all measurements were taken using one particular setting of embouchure control parameters, chosen to play F_3. For the first pair of instruments the embouchure was optimised for the ophicleide(2157) and for the second pair of instruments the embouchure was optimised for the saxhorn basse (3812). This process and its consequences are discussed in section 6.2.9. Care was taken not to disturb the position of the mouthpiece relative to the lips, particularly when changing between instruments as this has been shown to be the main source of variation in the embouchure (see chapter 3).

6.2.6 Threshold pressure

Table 6.1 and table 6.2 give values for the threshold level of overpressure in the mouth needed to initiate oscillation and sound the first and second pairs of instruments, respectively. All experiments showed small variations in the required threshold pressure when changing between fingering patterns or valve combinations. Activation of the 4th valve consistently required a higher threshold pressure of 1 or 2 mbars. No clear pattern was observed in the variation with different fingering patterns with the ophicleide, though the size of the variations was fairly consistent with a range of approximately 2 mbar. During the experiments with the first pair of instruments the threshold pressure required to sound the ophicleide was consistently less than that required to sound the saxhorn. For the experiments with the second pair of instruments the reverse was true in that the ophicleide required a significantly higher mouth pressure to sound than the

Table 6.1: Threshold mouth pressures for the first pair of instruments using embouchure optimised for the ophicleide (2157).

Instrument	Pressure(mbar)
Ophicleide (2157)	
$B\flat_1$	6.5±0.5
F_2 vented	5.5±0.5
F_2 unvented	5.0±0.5
Bass saxhorn (4273)	
V0	7.3±0.1
V4	9.0±0.1

Table 6.2: Threshold mouth pressures for the second pair of instruments using embouchure optimised for the Saxhorn Basse (3812).

Instrument	Pressure(mbar)
Ophicleide (4287)	
C_2	12.5 ±0.1
G_2 vented	11.0 ±0.5
G_2 unvented	12.8 ±0.5
Saxhorn basse (3812)	
V0	8.3±0.1
V4	9.0±0.1

saxhorn basse; possible reasons for this are discussed in section 6.2.9.

6.2.7 Pitch variation with pressure

For both B♭ instruments, a stable sounding regime was present over a wide variation in pressure difference across the lips (typically 7 - 15 mbar). At higher pressures instability was evident with an onset of multiphonic response. Figure 6.2

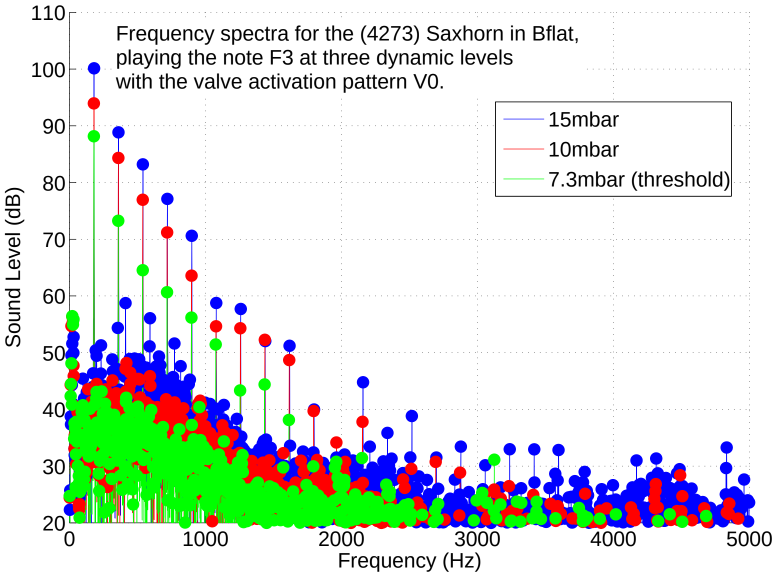


Figure 6.2: Frequency spectra for the bass saxhorn (4273) with no valves operated (VO) playing F_3 with three different mouth pressures.

shows three examples of spectra for different mouth pressures, for the saxhorn in B♭ with no valves activated (V0). The spectrum of the note played at 15mbars displays evidence the multiphonic behaviour in the form of extra peaks not harmonically related to the fundamental. Further investigation of this behaviour is needed to ascertain differences in playing stability for different fingerings and valve combinations, but this would make an interesting extension to this study.

Analysis of the radiated sound spectra showed there were significant differences in the pitch variations produced by changing the supply (mouth) pressure. For the saxhorn in B♭, the frequency of the fundamental rose by no more than 2Hz from threshold playing pressure up to 20mbar. For the $B\flat_1$ fingering on the ophicleide the playing frequency rose by similar amounts, but by around 4Hz for the F_2 vented fingering, and up to 10 Hz for the F_2 unvented fingering.

Results for the second pair of instruments show similar behaviour. Again there was very little (less than 1Hz) pitch variation with mouth pressure for the saxhorn basse. For the ophicleide in C there was progressively more pitch variation from the C_2 fingering to the G_2 vented to the G_2 unvented (up to 4 or 5Hz) though overall the magnitudes of these pitch variations were less with the C ophicleide than with the B♭ ophicleide. This may be due to the smaller range of playing mouth pressures due to the higher threshold pressure. In contrast to the B♭ instruments the playing frequency decreased with increasing mouth pressure.

6.2.8 Variation with fingerings and valve combination

The saxhorn in B♭ showed only small pitch variations between notes played with the two different valve positions. There was, however, a significant decrease (around 5dB) in sound level (for constant supply pressure) when operating the 4th valve. To produce the same sound level (86dB) a supply pressure of 8mbar was needed with no valves operated and 10mbar with the 4th valve operated.

Figure 6.3 shows the frequency spectra for these sounds, with little variation between the two. In contrast the ophicleide exhibited significant variations in the radiated sound for same sound level (85dB) played with the three fingerings as shown in figure 6.4. It was observed that there was a slight difference in sounding pitch between the two F_2 fingerings and a perceptible difference in sound quality from the relative position to the instrument of a player, but much less difference when heard from a position on the axis of the bell. This suggests that venting has less effect than players might expect.

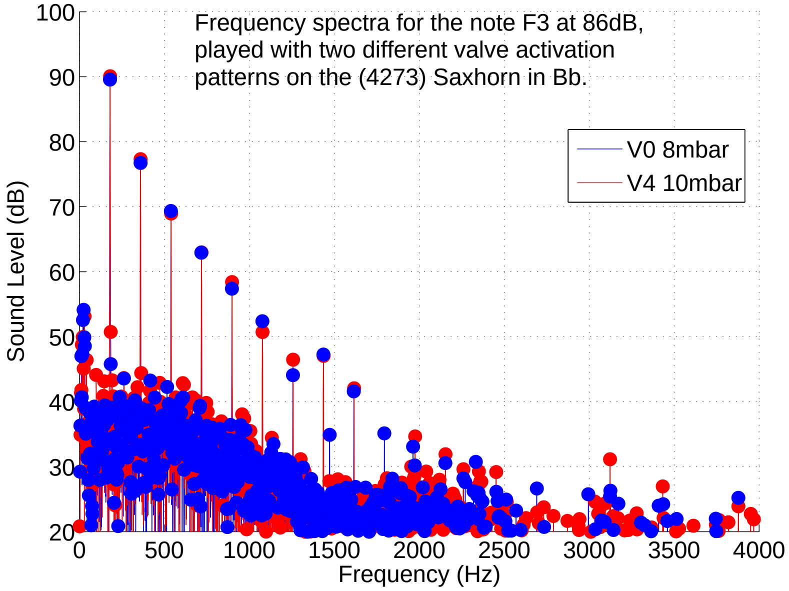


Figure 6.3: Frequency spectra for the saxhorn in B♭ (4273) playing F_3 at same sound level for two valve positions.

Results for the second pair of instruments show similar behaviour. Again there was a decrease in sound level (between 3dB and 5dB) when operating the 4th valve on the saxhorn basse. Again there were only small pitch changes between the two valve positions and very small spectral variations; typically less than 2dB variation between equivalent harmonic peaks (see figure 6.5). Sound levels did not vary significantly (less than ± 1dB) when changing between the three fingering patterns on the ophicleide in C. However the spectral variations were

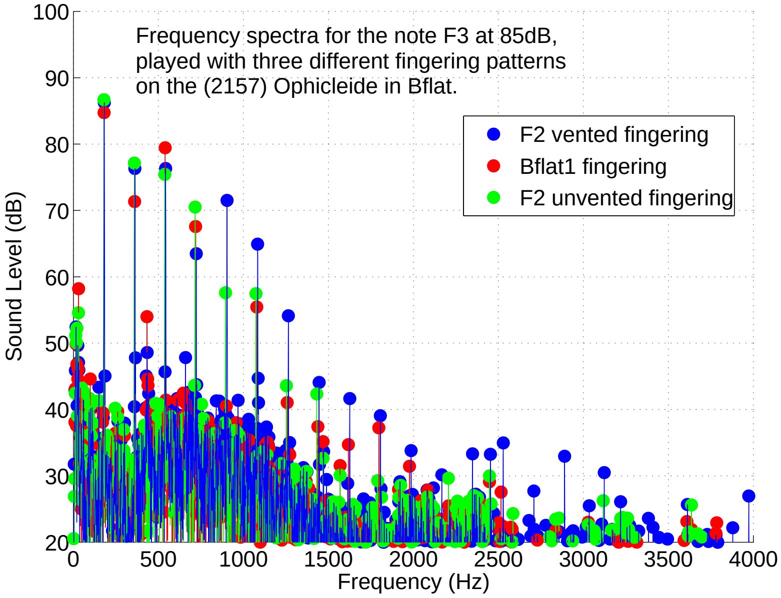


Figure 6.4: Frequency spectra for the ophicleide in B♭ (2157) playing F_3 at same sound level for three fingering patterns.

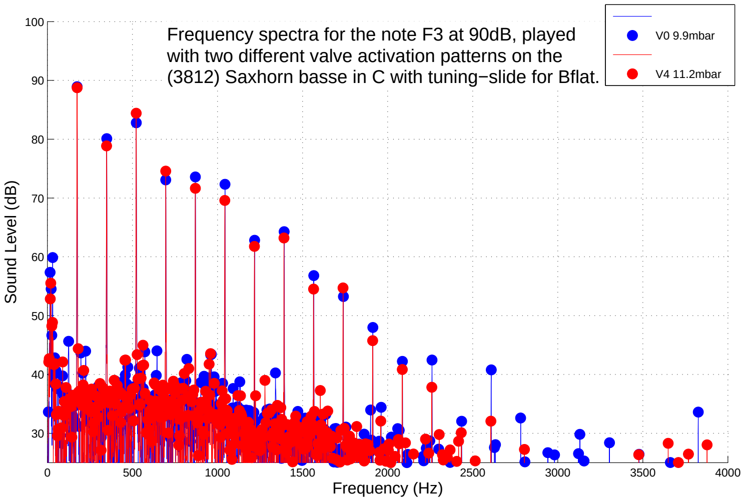


Figure 6.5: Frequency spectra for the saxhorn basse (3812) playing the note F_3 at the same sound level (90dB) with two different valve positions.

much more significant than those obtained with the saxhorn with the magnitude of peaks varying by around 10dB as shown in figure 6.6.

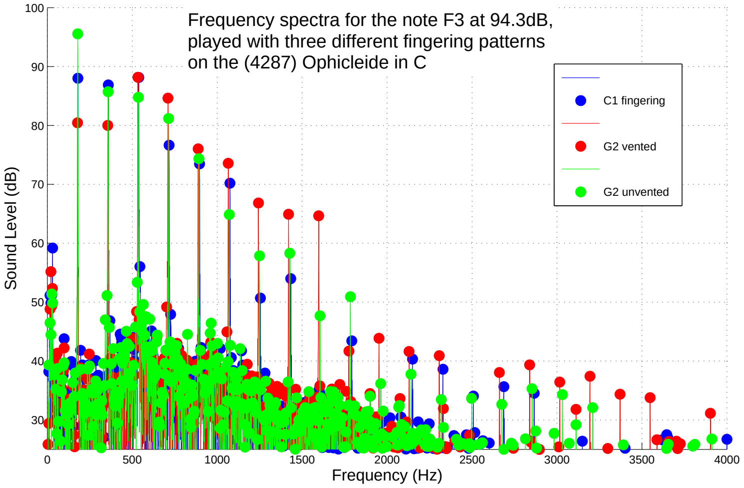


Figure 6.6: Frequency spectra for the ophicleide in C (4287) playing the same note with three fingering patterns at the same sound level (94dB).

6.2.9 Discussion - embouchure suitability

The choice of suitable embouchure parameters is an important consideration in designing a comparative study. The embouchures used have been chosen by making adjustments to the control parameters until a realistic sound was obtained for the the pair of instruments being compared. The threshold mouth pressure required to sound a particular instrument varied with the embouchure parameters chosen. One measure of the suitability of the embouchure, used during the process of setting the embouchure parameters, was the threshold pressure required. It is assumed that a real player would adapt their embouchure to minimise the blowing pressure needed to sound the instrument [76]. In order to mimic this process when setting the embouchure parameters the threshold pressure was noted and adjustments made to minimise this where possible. The stability of the playing frequency over the range of sound levels was also used as a measure of the embouchure suitability. By these measures it was not possible to find one particular embouchure that was most ‘suitable’ for both the ophicleide and the saxhorn. The measurements presented were obtained by optimising the embouchure for the ophicleide (2157) for comparison with the saxhorn (4273) and for the second set of measurements the embouchure was optimised for the saxhorn basse (3812) for comparison with the ophicleide (4287). It was not unexpected that the threshold pressures were lower for the instrument for which the embouchure was optimised. It was noted that the magnitudes of the playing frequency variations (with changing mouth pressure) were also embouchure dependant. Nevertheless, the relative variations, between different fingering patterns on the ophicleides and valve combinations on the saxhorns, remained consistent whatever embouchure was used. This observation is in agreement with the findings of Petiot for the trumpet [76].

6.2.10 Conclusions

The operation of the 4th valve on the saxhorns had very little effect on the spectrum of the sound produced in contrast to the ophicleides which displayed significant spectral variations between notes produced with different fingering patterns. There are several non-acoustical reasons for the demise of the Ophicleide, including difficult playing technique and problems with damage and maintenance [70]. Results from these experiments support claims that, like other instruments with large tone holes, there are significant variations in tone quality with different fingering patterns.

6.3 The bass trumpet

The bass trumpet is pitched either in C or B♭ one octave lower than the common trumpet. These instruments are generally played by trombone players and the tenor valve trombone appears to be a very similar instrument (also pitched in C or B♭) though the playing experience is reportedly different [71].

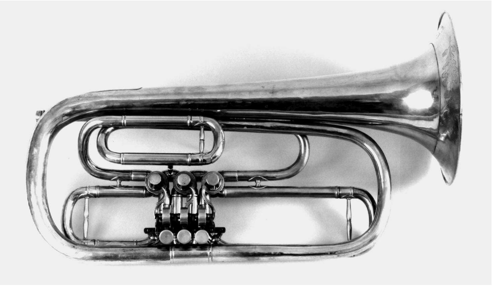


Figure 6.7: EUCHMI (4045) Bass trumpet in 9-ft B♭ (Robert Schopper, Leipzig, c 1910).

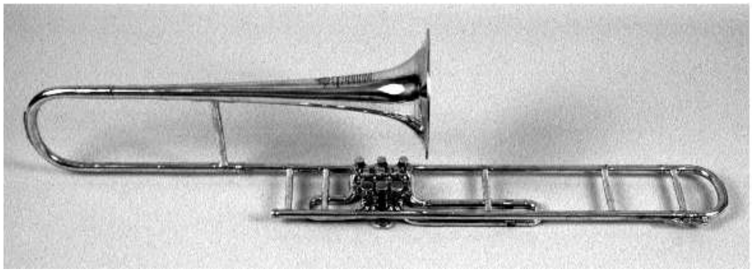


Figure 6.8: EUCHMI (3830) Valve tenor trombone in B♭ (Zimmermann, St Petersburg, c 1905).

6.3.1 Instruments

A total of four bass trumpets were investigated and compared to a valve trombone and a slide trombone. The trombones and the three bass trumpets in B♭ are of German and east European origin and were supplied by the Edinburgh University Collection of Historic Musical Instruments [68]. The Bass trumpet in C was on loan from a musician (William A. Giles).

The sample set consisted of:

- EUCHMI (3847) Bass trumpet in B♭ (Schuster, Markneukirchen, c 1900)
- EUCHMI (4045) Bass trumpet in B♭ (Schopper, Leipzig, c 1910)
- EUCHMI (2858) Bass trumpet in B♭ (V.F. Cerveny, Koniggraetz, c 1900)
- WAG (1) Bass trumpet in C (Alexander, Mainz, 1983) with first valve operated
- EUCHMI (3753) Tenor slide trombone in B♭ (Mitsching-Alschausky, W.-Elberfeld, Germany, mid 20th century)
- EUCHMI (3830) Valve trombone in B♭ (Zimmermann, St. Petersburg, c 1905)

In order to allow direct comparison between instruments with the minimum of embouchure variation all measurements were made using the same mouthpiece (EUCHMI 1586). The main tuning-slides were adjusted so that the instruments when played by a human player sounded F_3 at 20 cents below $A_4 = 440$ Hz equal temperament. Again this was to allow direct comparison between instruments and to maximise the suitability of the single embouchure used for each complete set of measurements.

6.3.2 Experimental setup

Figure 6.9 shows the experimental apparatus with one of the bass trumpets in position. The apparatus is very similar to that described above in section 6.2.4 and the method is as described in section 6.2.5.

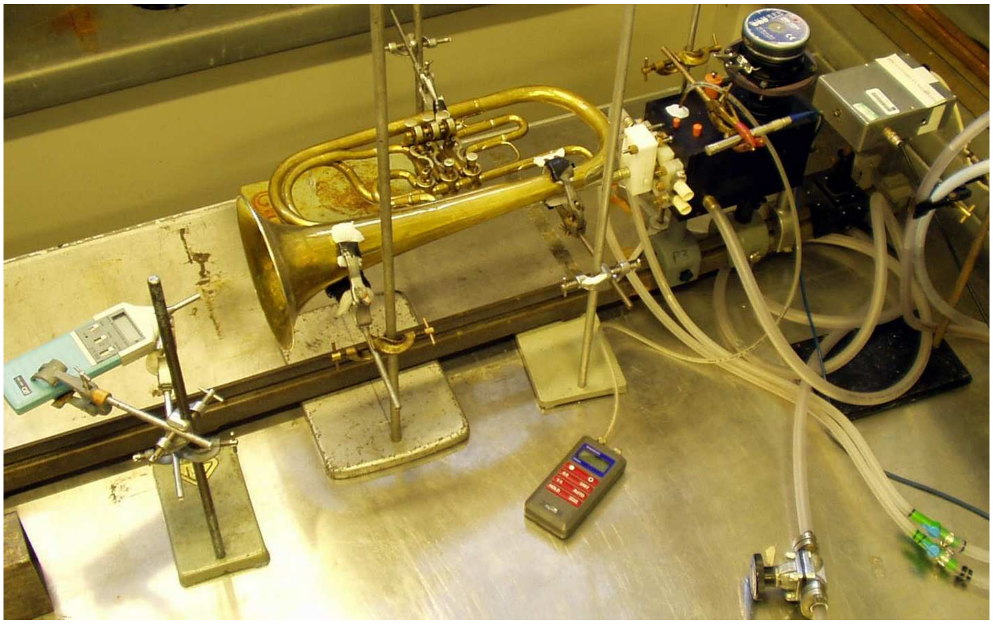


Figure 6.9: Experimental apparatus with bass trumpet.

6.3.3 Improvements to mouth-piece holder

As shown in chapter 3 the previous design of mouthpiece holder was not sufficient to prevent measurable changes to the embouchure as the mouthpiece is reconnected to an instrument. A new mouthpiece holder was designed to provide greater support and control so minimising the effect on the embouchure of numerous changes between instruments. Photographs of the new design are given in figure 6.10. The inner section of the mouthpiece holder (in black) was made specifically for the shape of the particular mouthpiece used. This in combination with the four plastic fixing screws allowed the mouthpiece to be firmly clamped in place against the artificial lips so as to maintain the stability of the embouchure throughout each series of measurements.

Figure 6.10: New mouthpiece holder; showing removable central section and stabilising screws.

Reproducibility of the embouchure

After each instrument had been played and disconnected from the mouthpiece the response of the lips to an acoustic driving pressure was measured. The procedure was similar to that described in chapter 3 with slight modification. The mouthpiece used is a museum piece and therefore it was not possible to use the probe microphone to measure the driving pressure as this requires the drilling of a 2mm channel in the mouthpiece cup. It was therefore necessary to use the speaker mounted on the main body of the artificial mouth (this can be seen in figure 6.9) and measure the driving pressure in the mouth cavity using a Brüel and Kjær $\frac{1}{4}''$ microphone. The PULSE system was used for the signal processing as before.

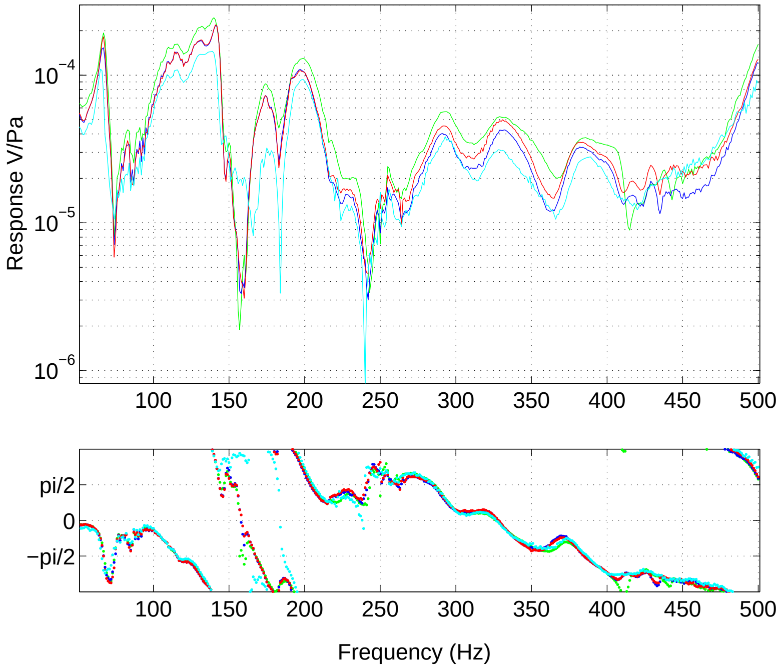


Figure 6.11: Reproducibility of lip response measurements when using new mouthpiece holder.

Figure 6.11 gives three example response curves. The frequencies of the resonance peaks are well reproduced and the standard deviations of the quality factors of the resonance peaks are around 1.4. This is significantly less variation than with the previous mouthpiece holder where reconnecting mouthpiece and instrument produced standard deviation of the quality factors of 3.0. (Note that previous results showed that the inherent variations due to the measurement system resulted in standard deviations of the quality factors of 0.8). The results for the previous mouthpiece holder are discussed in chapter 3 and shown in figure 3.12.

6.3.4 Mouth pressure considerations

The relationship between the applied mouth overpressure and the level of the sound output was investigated for each instrument. For each complete set of measurements with one embouchure (optimised for a particular instrument) there was little variation in the threshold mouth pressure required to sound each instrument. The sound levels produced by a given mouth pressure varied between instruments but there were no significant differences to distinguish between instrument species.

6.3.5 Spectral analysis

Measurements were carried out in a laboratory and not an anechoic chamber therefore the position of the instruments (determined by the position of the connection to the mouthpiece) in the room were kept constant throughout these measurements. While sounding the instruments with the artificial lips, the radiated sound was recorded at a point on the axis of the bell and at a distance of one bell radius from the plane of the bell; the sound level was also measured at this position. The radiated sound was also recorded in a position corresponding the location of a player's ear in normal playing position. There is a high noise level at this position caused by air leakage at the artificial lips, limiting the useful frequency range of these 'ear' position measurements to approximately 3kHz. Improvements in design may help with this and allow more detailed study of the radiated sound close to the artificial mouth. The normalised spectral centroids were calculated with a program provided by Beauchamp [12] using the first 30 harmonics. It is generally accepted that differences higher than 0.2 units in normalised spectral centroid should be perceptible [59]. The spectra for the sound measured at the bell indicate no clear difference between instrument species; three examples are given in Figure 6.12. Values for the spectral centroid num-

Table 6.3: Normalised Spectral Centroids, bell and 'ear' position, no valves operated

	Bell	'Ear'
Valve trombone (3830)	3.55	4.3
Slide trombone (3753)	3.75	4.8
Bass trumpet (3847)	3.4	4.3
Bass trumpet (4045)	3.45	4.0
Bass trumpet (2858)	3.4	3.7
Bass trumpet (WAG1)	3.9	5.5

bers are given in table 6.3 and these confirm that there is no clear distinction between instrument species (the Alexander bass trumpet (WAG1) having the brightest sound followed by the trombones and then the other bass trumpets). When measured at the 'ear' position, results are similar, with the brightness of the sound varying slightly between instruments (the Alexander again having the brightest sound) but with no clear distinction between instrument species. The measurements were repeated with the 1st and 3rd valves operated (4th for the bass trumpet in C with the 1st valve already operated). The necessary valve tuning-slides were adjusted so that the instruments when played by a human player again sounded F_3 at c 20 cents below $A_4 = 440$ Hz equal temperament. The slide trombone (3753) was omitted from these measurements. The results for this V13 valve combination were similar: the spectral centroid numbers showing slight variations in brightness but with no clear distinction between instrument species (again the Alexander having the brightest tone measured at the bell, though not at the 'ear'); see table 6.4.

Table 6.4: Normalised Spectral Centroids, bell and 'ear' position, V13

	Bell	'Ear'
Valve trombone (3830)	3.4	4.3
Bass trumpet (3847)	3.6	5.0
Bass trumpet (2858)	3.4	3.8
Bass trumpet (4045)	3.75	5.5
Bass trumpet (WAG (1))	4.0	4.5

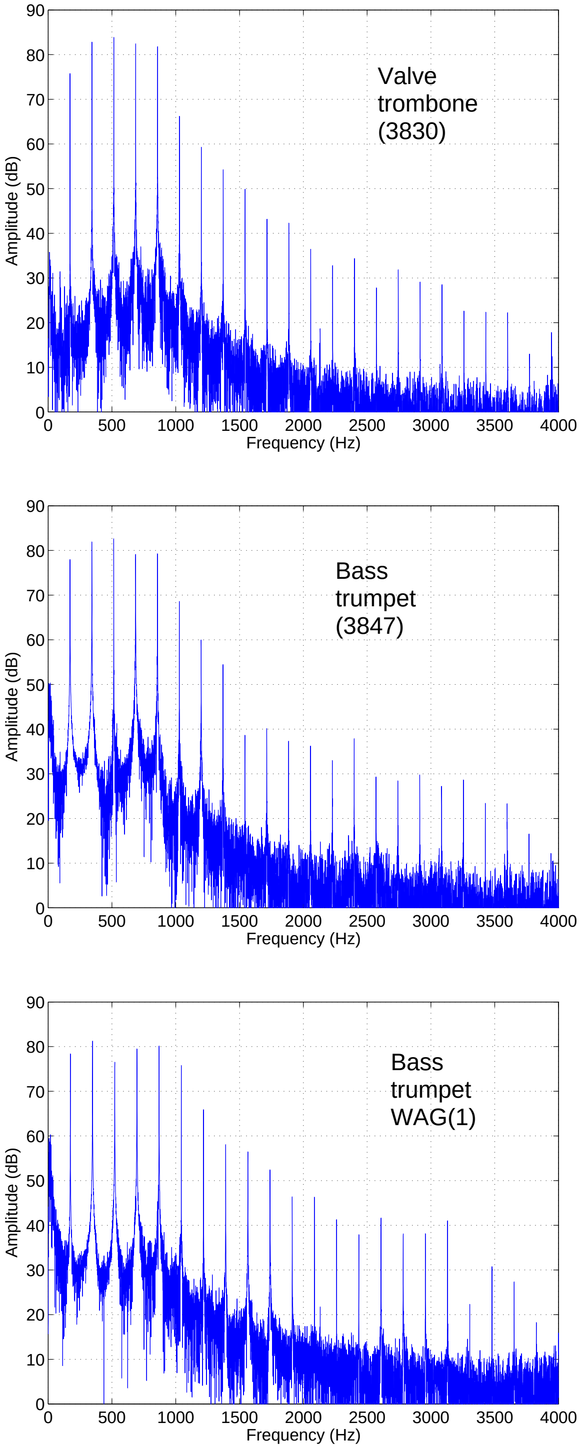


Figure 6.12: Spectra of radiated sound measured at the bell for three instruments playing the same note at the same sound level.

6.3.6 Impedance measurements

The input impedance of each instrument was measured using the *BIAS* system [8], with the same valve and slide settings as above (no valves operated for the B♭ instruments, the first valve operated for the C instrument). Figure 6.13 shows peak envelopes of the input impedance curves, the data for the trombones is marked with circles.

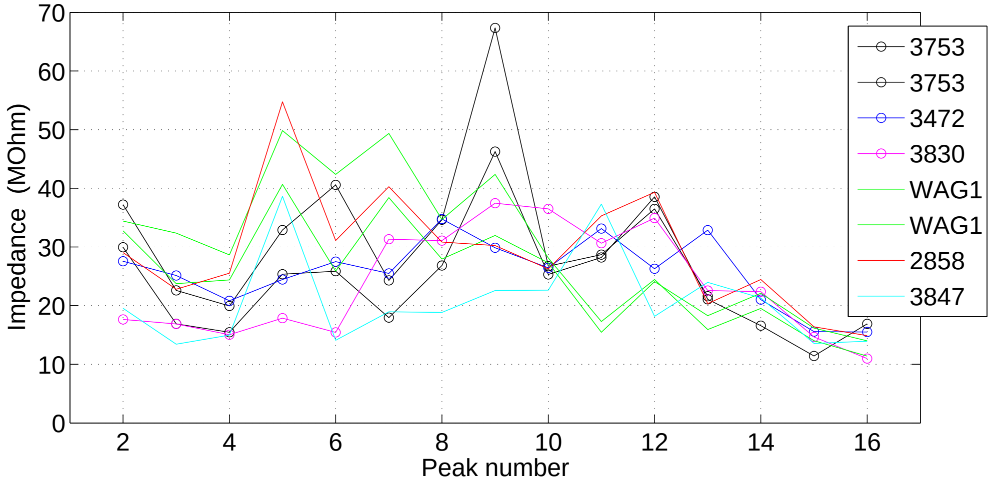


Figure 6.13: Envelopes of the acoustic impedance peaks.

The equivalent fundamentals of the modes [29] (indicating the harmonicity of the modes) were fairly consistent for all specimens, apart from some significant variation for the second mode, see figure 6.14. This method can successfully distinguish between instrument species [71], but did not in this case. The differences seen between bass trumpets and trombones are of the same order as the differences seen between bass trumpets.

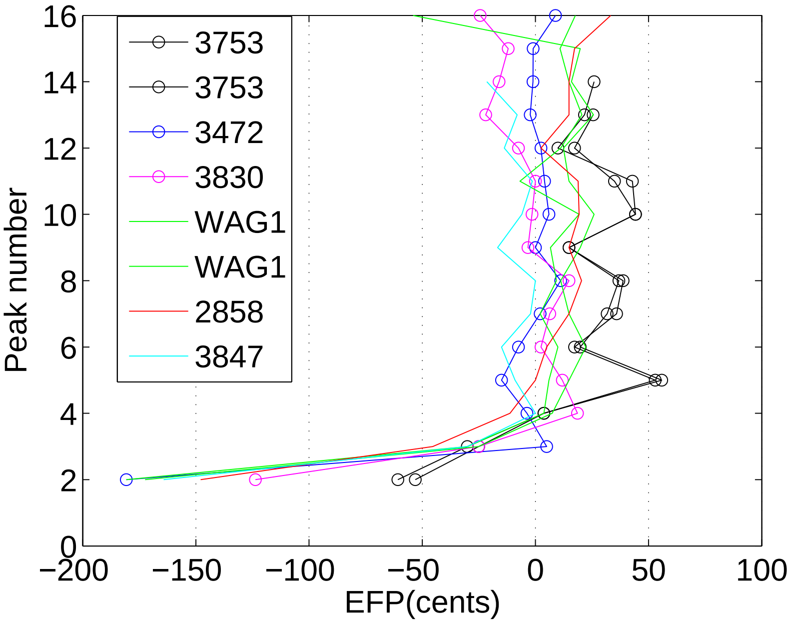


Figure 6.14: Equivalent fundamental pitch (in cents relative to B$\flat_1$) of the first sixteen modes of vibration of the sample set.

6.3.7 Discussion

These measurements form part of a larger study which includes physical measurements of the bores of the instruments. The results of these [71] indicate that the bores of the instruments have parameters which are in overlapping ranges. This is in agreement with the results of the spectral and impedance measurements which show no clear distinction between bass trumpets and valve trombones.

The acoustical differences, if they exist, between instrument species are subtle; the only obvious physical difference is in the shape or wrap of the instrument. Further investigation of the sound at a variety locations relative to the player may reveal the extent to which these physical characteristics affect the sound produced. The current design of the artificial mouth is limited in this respect in that the noise level close to the lips is significant.

These experiments were carried out using a single mouthpiece in order to maintain the consistency of the embouchure. It seems likely that the player's choice of mouthpiece and their own playing style has a more significant affect on the quality of the sound produced than the choice of bass trumpet or valve trombone.

6.4 Conclusions

The development of artificial mouths has been an important advance in both objective and subjective methods of investigating instruments. When using musicians the inherent variations make it difficult to make controlled investigations and the greater control and reproducibility of the embouchure of the artificial mouth is an advantage in comparative studies. The suitability of the chosen embouchure for different instruments, valve activations, or fingering patterns is an important issue in the development of comparative studies. Results suggest that although any given embouchure is not equally optimised for several instruments, or even different fingering patterns on the same instrument, useful results are nevertheless obtained. This question of suitability of the embouchure for a particular instrument is itself a very interesting problem and would be an interesting area of future research. An investigation of the resonance behaviour of the artificial lips during the optimisation of the embouchure for a range of instruments would be a particularly interesting study.

Chapter 7

Conclusions and future work

7.1 Reproducibility and control

In chapter 3 factors affecting the reproducibility of the embouchure of the artificial mouth were investigated. Repeated measurements were made of lip resonances and sources of variation identified. It was found that the frequencies of the lip resonances are generally well reproduced for repeated resetting of the embouchure parameters. Significant variations were observed in the magnitude and quality factor of resonances under conditions where the mouthpiece was removed and replaced against the lips. Smaller variations were observed when the mouthpiece was kept in contact with the lips and the speaker box (representing the instrument) was repeatedly removed and reattached to the mouthpiece shank. Several reasons for these variations were discussed. Recommendations for procedures to minimise these variations and improvements to the design were suggested.

7.2 Visualisation studies

A high speed camera was used to visualise the lip opening to provide detailed information on the behaviour of the lips of brass players. A number of players and a wide range of notes were investigated. Image analysis provided quantitative information on the dimensions of the lip opening. Comparisons were made between the behaviour of the artificial lips and those of the musicians. The definition of a function relating area and height, useful in modelling, was explored.

7.2.1 Describing the lip opening

Investigation of the behaviour of the lip opening has shown that, in agreement with the results of previous studies, the amplitude of lip motion increases with increasing sound level and decreasing frequency. The magnitude of the lip oscillation was found to vary between nominally similar notes when played by different musicians or different embouchures on the artificial mouth. The general features of behaviour were, however, consistently reproduced. The height and area of the lip opening varied smoothly over the course of each cycle of oscillation. The width of the opening often varied less smoothly displaying regions of almost constant value at maximum opening. The extent to which this behaviour was evident depended on pitch and sound level and was most obvious for low pitched loud notes.

7.2.2 The area-height function

Values were obtained for the exponent q in the general area-height function $S(t) \propto h(t)^q$. The results from musicians have shown that as the amplitude of lip oscillation decreases, whether it is due to an increase in pitch or a decrease in sound level, there is an increase in the value of the exponent q (in most cases between $q = 1$ and $q = 2$). The results from the artificial lips show a similar relationship for variations in pitch, however changes in sound level do not appear to affect the exponent q. Noticeable timbral differences between sounds produced with the exponents $q = 1$ and $q = 1.5$ have been reported by Gilbert *et al* [51].

Analysis has identified a number of distinct regions of behaviour within a cycle of oscillation corresponding to different values of the exponent q. This suggests that a single value of q is not sufficient to represent the full detail of the behaviour.

7.2.3 Extremely loud playing

Results show that during extremely loud playing the lip motion is qualitatively similar to quieter notes. This suggests that the lip motion is not the origin of the dramatic increase in the levels of the high harmonics in the radiated sound.

7.3 Transient behaviour

An adaptation of the visualisation technique was applied to the study of the motion of the brass player's lips during the initial transient of a note. The technique used was shown to be useful in relating the lip motion to the transient in the mouthpiece pressure waveform. The effect of the length of the horn on the nature of the transient was studied. Changes in the mouthpiece pressure waveform and in the behaviour of the lip motion have been observed at a time corresponding to the measured round trip time for each length of instrument.

7.4 Historic instrument comparisons

The artificial mouth was used to play a number of historic instruments for comparative purposes. As suggested by the reproducibility measurements in chapter 3, the same mouthpiece was used and retained in position between measurements to minimise unwanted alterations to the embouchure.

7.4.1 Ophicleide and saxhorn

Two ophicleides and two saxhorns were compared. It was found that the operation of the 4th valve on the saxhorns had very little effect on the spectrum of the sound produced. In contrast, the ophicleides displayed significant spectral variations between notes when different fingering patterns were used.

7.4.2 Bass trumpets

Four bass trumpets were investigated and compared to a valve trombone and a slide trombone. For this study a new design of mouthpiece holder was used. Results of the spectral and impedance measurements revealed no clear distinction between bass trumpets and trombones. It was concluded that the player's choice of mouthpiece and playing style has a more significant affect on the quality of the sound produced than the choice of bass trumpet or valve trombone.

7.4.3 Use of the artificial mouth as a tool for comparative studies

This study has shown that the suitability of the chosen embouchure for different instruments, valve activations, or fingering patterns is an important issue in the development of comparative studies. Although any given embouchure is not equally optimised for several instruments, or even different fingering patterns on the same instrument, useful results can nevertheless be obtained.

7.5 Future work

Improvements to the design of the artificial mouth could include alternative designs of lip guides. These are currently being developed [75] with the aim of providing more control of the lip position whilst retaining the ease of access and flexibility of a variety of embouchures. The current design of the artificial mouth suffers from air leakage at the lip edges. Because of this the noise level close to the lips is significant. New lip guide designs should address this problem.

The development of a realistic tongue mechanism for the artificial mouth [82] would allow investigation of transient behaviour without the variability inherent in human playing. This could allow consistent testing of instruments looking at, for example, the ease of starting a note. A further development could also focus on relating the initial playing frequency to the form of the transient.

The observed changes in the transient envelope of the mouthpiece pressure occur on a timescale which is significant when compared with the overall transient length. It is therefore expected that these differences would be perceptible to the human ear. Listening tests on recorded radiated sounds, and/or synthesised versions of sounds incorporating the measured effects, would be an interesting extension of this work.

Many aspects of the behaviour that have been identified in this work could be incorporated into physical models of brass player's lips. In particular models could include a frequency and sound level dependent form of the relationship between the lip separation and opening area. Future developments could additionally utilise a form of this relationship which varies during each cycle.

The question of suitability of the embouchure for a particular instrument would be an interesting area of future research. An investigation of the resonance behaviour of the artificial lips during the optimisation of the embouchure for a range of instruments would be a particularly interesting study.

Appendix A

Additional plots

The following are some further example results.

Figure A.1 shows the logarithmic area-height plot for a particularly low frequency, high sound level note on the artificial lips. Here the exponent q is in the range 1-1.1. There is some hysteresis evident for this data.

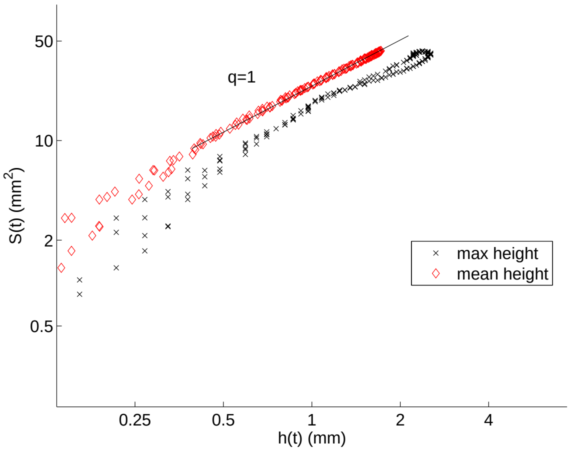


Figure A.1: Logarithmic area-height plot for Artificial Mouth playing mouthpiece only, 150Hz, 110dB

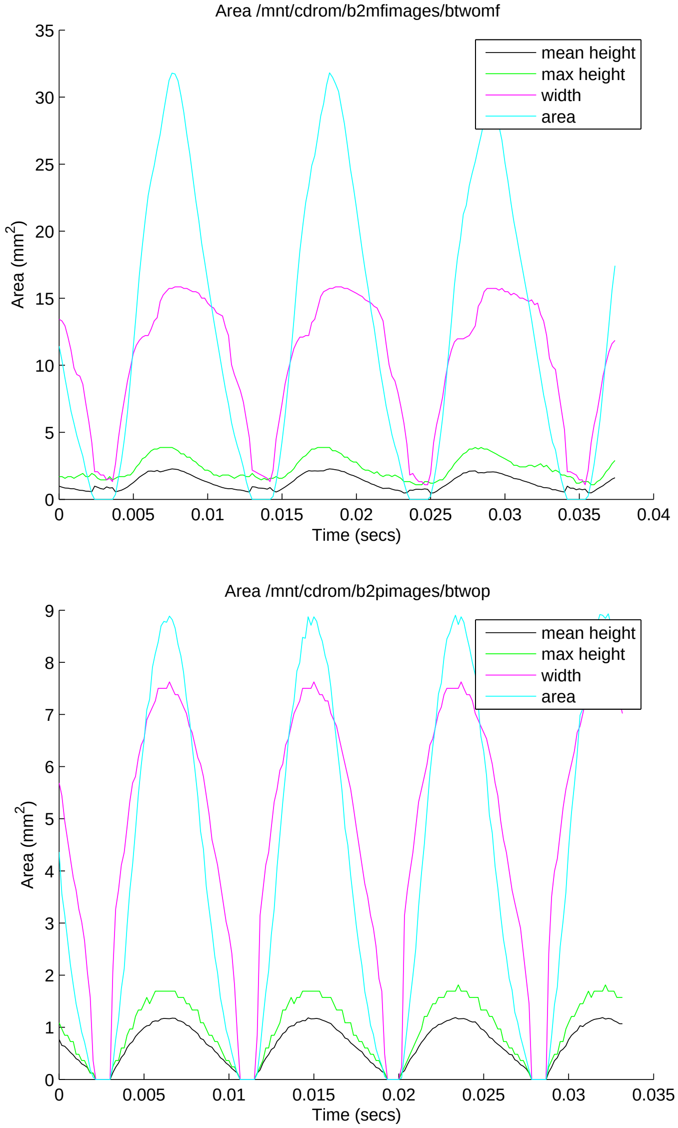


Figure A.2: Area, height and width as a function of time, Player A B$\flat_2 mf$ 95dB(left), B$\flat_2 p$ 86dB(right)

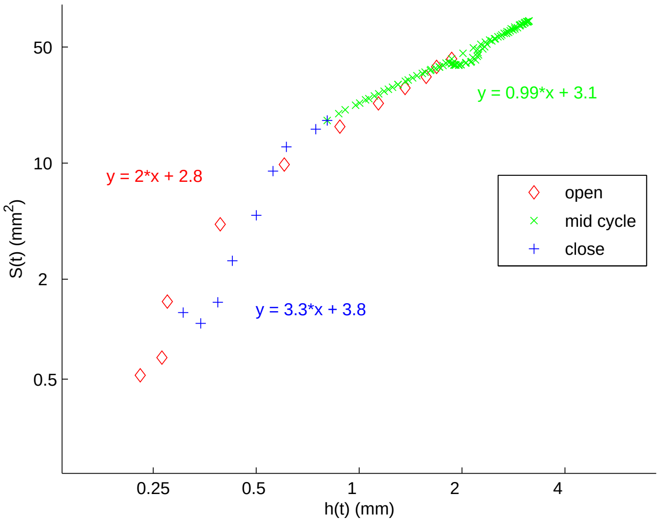


Figure A.3: Logarithmic area-height plot showing Player AJ, note B$\flat_1$*ff*

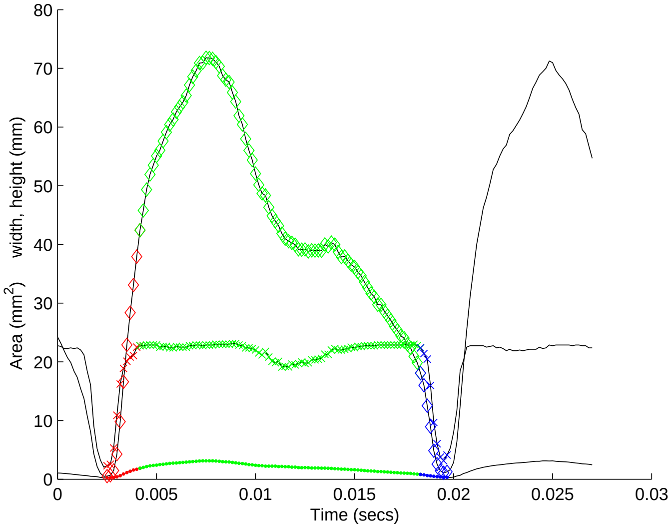


Figure A.4: Area, mean height and width against time, Player AJ, note B$\flat_1$*ff*

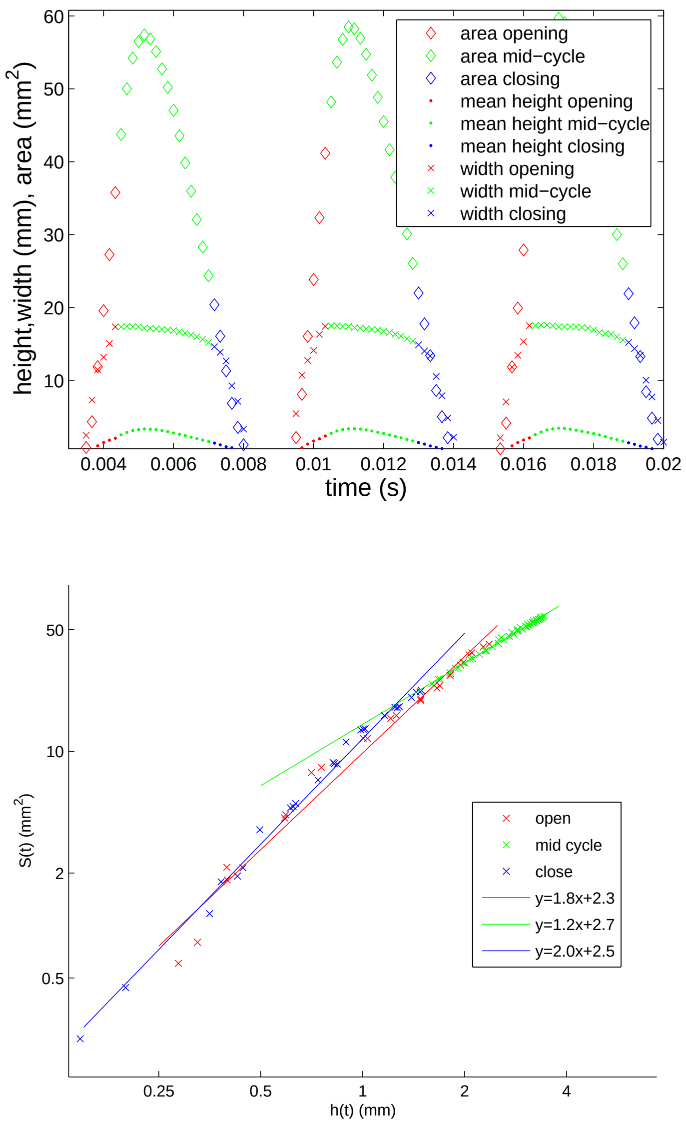


Figure A.5: (Player J, note F3*ff* (left) Area, mean height and width against time (right) Logarithmic area-height plot

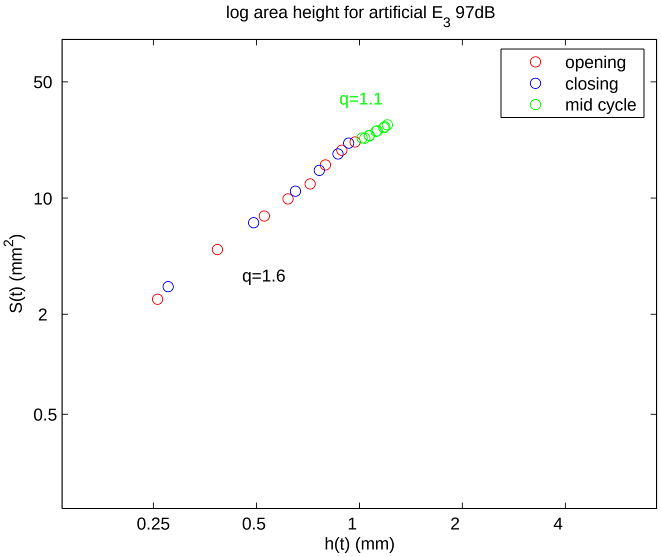


Figure A.6: Logarithmic area-height plot for the artificial mouth playing note E_3 at 97dB

Appendix B

Additional images

The following figure shows a further example of a series of lip images.

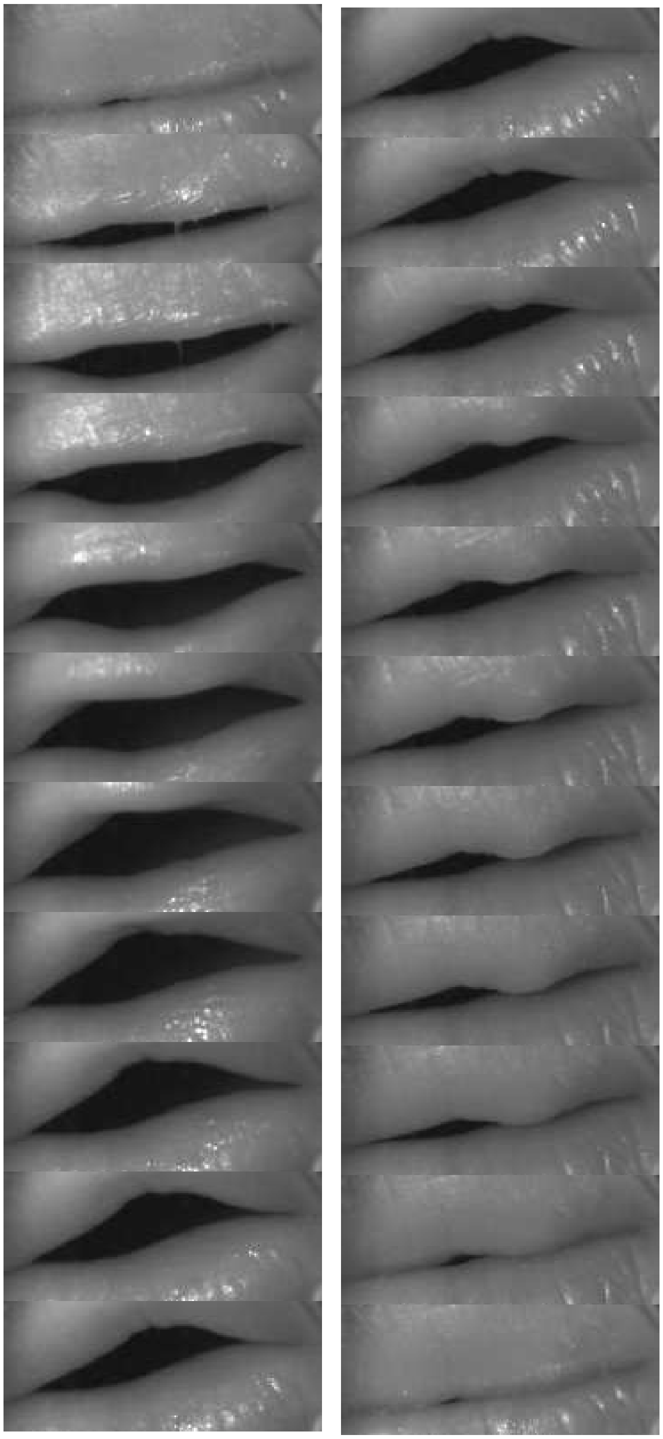


Figure B.1: Lip images for Player A, note B$\flat_1$ *mf*, corresponding to the data given in figure 4.32 (left).

Appendix C

Films

The attached CD contains the following films:

1. $B\flat_1 p$, player A
2. $B\flat_1 mf$, player A
3. $B\flat_1 ff$, player A
4. $B\flat_1 mf$, player S
5. $A_1 p$, player M
6. $F_4 mf$, player A

7. $B\flat_2 mf$, artificial mouth

8. E_3, artificial mouth embouchure 1
9. E_3, artificial mouth embouchure 2
10. E_3, artificial mouth embouchure 3

11. E_3, artificial mouth embouchure 1, 7mbar

12. E_3, artificial mouth embouchure 1, 8mbar

13. E_3, artificial mouth embouchure 1, 10mbar

14. E_3, artificial mouth embouchure 1, 12mbar

15. E_3, artificial mouth embouchure 1, 14mbar

16. E_3, artificial mouth embouchure 1, 16mbar

17. E_3, artificial mouth embouchure 1, 18mbar

18. E_3, artificial mouth embouchure 1, 20mbar

19. E_3, artificial mouth embouchure 1, 22mbar

20. E_3, artificial mouth embouchure 1, 24mbar

21. E_3, artificial mouth embouchure 1, 26mbar

22. E_3, artificial mouth embouchure 1, 28mbar

23. E_3, artificial mouth embouchure 1, 30mbar

24. $B\flat_1$, player J, Brassy

25. $B\flat_1$, player J, Non-Brassy

26. F_3, player J, Brassy

27. F_3, player J, Non-Brassy

28. D_4*fff*, player J, Brassy

29. $D_4 f$, player J, Non-Brassy

30. D_4*mf*, player J,

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