Experimental Investigations of Lip Motion in Brass Instrument Playing

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Abstract

The precise nature of the motion of the lips of the musician is critically important to the sound of the brass wind instrument. The player must match the oscillation of the lips to the acoustical properties of the instrument and it can take many years of practice to master the techniques involved. Visualisation techniques for capturing the motion of the lips during performance are described and the behaviour of the lips quantitatively analysed using digital image analysis. The concept of an artificial mouth for the sounding of brass wind instruments is discussed and the motion of the artificial lips is compared to that of human musicians.

When a brass instrument is played loudly the energy of the higher harmonics increases, creating a distinctive 'brassy' timbre. It has been suggested that saturation or constraint of the lips of the musician during extremely loud playing is responsible for this change in sound. Measurements of the motion of the lips of a number of different musicians on different instruments suggest that the lips are not significantly constrained at any playing dynamic, and that it is the phenomena of nonlinear propagation and shockwave generation that is responsible for the increase in energy of the higher harmonics.

It is widely accepted that the starting transient of a musical instrument is of great importance to both listener and musician. Previous studies of brass instruments have focused on the steady-state behaviour of the lip-instrument interaction. Measurements of the motion of the lips have been synchronised with the pressure in the mouthpiece of the instrument and the sound radiated from the bell in order to investigate the transient behaviour of the system during both the starting transient and slurs between notes. This work has been extended to include measurements of the pressure in the mouth of the player during the starting transient, and this information used to recreate realistic transients using an artificial mouth. The transient behaviour of the system is clearly affected by the time delay between the start of the note and the acoustical feedback from the instrument beginning. The information obtained can be used to aid in the creation of accurate computational and physical models of brass wind instruments.

Declaration

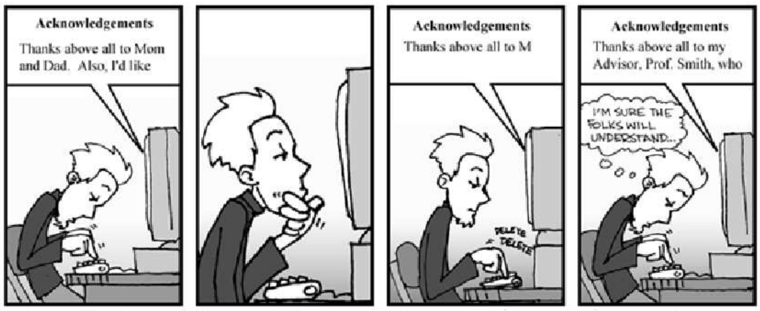
I do hereby declare that this thesis was composed by myself and that the work described within is my own, except where explicitly stated otherwise.

Samuel DF Stevenson
October 22, 2009

Acknowledgements

I feel a very unusual sensation—if it is not indigestion, I think it must be gratitude.'

–BENJAMIN DISRAELI



"Piled Higher and Deeper" by Jorge Cham www.phdcomics.com

In October 2000, two weeks before I moved to Edinburgh to begin my degree, I was given a rather tongue-in-cheek newspaper article about a mechanical trumpet player that some 'wacky scientists' at the University had designed and built.

...If only I'd known.

It conspires that 'chief wacky scientist', Professor Murray Campbell, was not only going to help me through two undergraduate projects but also to be kind enough to take me on as a postgraduate student. Murray's knowledge, infectious enthusiasm, and energy for acoustics—even after the lips had exploded for the umpteenth time—were boundless. Thank you.

Most of this thesis would not have been possible were it not for John Chick, who, as well as being a great horn player, was also willing to be a guinea pig on a seemingly infinite number of occasions. He has provided many ideas and

participated in many discussions, as well as not laughing at my many stupid questions about brass instruments. Thank you.

Sincere thanks go to Joël Gilbert for his endless enthusiasm and knowledge. Joël gave me many ideas about which direction to take my work, and I genuinely enjoyed his visits to Edinburgh. Seona Bromage spent more time than she had to helping me get started on all things 'lippy'. Michael Newton was an endless source of help, advice, and laughs. David Skulina and Jonathan Kemp let me pick their brains for Matlab titbits on a regular basis. Les Russell helped me out more often than I care to imagine. Thanks to you all.

4201 was a great place to spend 4 years of my life, mainly because of the other occupants—Mike, Rob, Darren, Dave, Seona, Lin, Ali, and Jonathan. Good luck to you all with whatever you do. I would probably never have finished this thesis without the support of my girlfriend Catriona, who has helped by providing tea, biscuits, hugs, and love when required (often). Reports of her wielding a pointy stick in my general direction have been greatly exaggerated. Thank you.

My biggest thank you is saved for all the musicians whose lips I have captured, poked, and prodded over the last four years. I genuinely couldn't have done it without your willingness to put yourselves through that. Thank you.

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Chapter 1

Introduction

'After silence that which comes nearest to expressing the inexpressible is music.'

—ALDOUS HUXLEY

It comes as a surprise to many that the brass wind instruments are still a topic of active scientific research. Modern orchestral instruments are descended from designs that are hundreds of years old and do not, at first, appear to present any great challenge to a physicist. They are—as a general rule—constructed from few (if any) moving parts and at heart consist of little more than a hollowed out cylinder which is open at both ends. Indeed, it is possible to fashion a rudimentary trumpet using little more than a garden hose.

Surely, then, such simple designs can be described in the simplest of terms? A player sounds a note by pressing his lips against one end of the instrument and buzzing them. The vibration of the lips couples to the instrument which, since it is mainly cylindrical, will have acoustic resonances with approximately harmonic frequencies. The buzzing sound made by the periodic motion of the lips is then strongly amplified if the frequency of the vibration corresponds to the resonance frequency of one of the acoustic modes of the instrument. We can then use basic Newtonian mechanics to describe the oscillations of the lips and of the air column within the instrument. What more can there be to say?

In this oversimplified case, the fundamental frequency of the tone produced by a brass instrument is a result of the linear coupling between the vibration of the lips of the musician and a given mode of the instrument. In reality, however, the coupling is not only nonlinear but takes place between the lips and *all* of the acoustic modes of the instrument. In addition, real brass instruments are not constructed from cylinders; instead they have a mouthpiece, flaring bell, valves or slides (or both), and non-cylindrical sections. To complicate matters further again, the instrument does not just amplify the buzzing of the lips. The lips vibrate and interact with the instrument, which in turn alters the vibrational behaviour of the lips. We shall see that the brass wind instruments are in fact highly nonlinear—the sound that is produced depends greatly on the precise form and amplitude of the input. It is simply not possible to reduce the role of the instrument to that of an amplifier.

Finally, we come to the lips themselves. When a musician wishes to sound a note on a brass instrument he forces air through his lips, causing them to periodically open and close. The most basic approximation that the physicist can make of an oscillatory system is that of a mass on a spring. Modelling the lips in this way has, in many ways, been very successful. However, the lips are made of soft tissue and the musician can greatly vary their shape, tension, and mechanical properties. During playing, each lip interacts not just with the oscillating air column in the instrument but also with the hard rim of the mouthpiece, the teeth of the player, and, indeed, the other lip. They move not in one dimension, but all three, and one section of the lip may move in one direction whilst a neighbouring part behaves differently. How many masses—and on how many springs—do you need to accurately describe the forced, damped oscillation of such a system? This thesis aims to investigate and quantify the behaviour of the lip-reed under a number of different playing conditions.

Much of the earliest work to try and describe the physical properties of wind instruments—of which the brass winds are but a part—was undertaken by Helmholtz [1877]. He attempted to classify the musical valves—or *reeds*—by their response to changes in pressure. Whilst the cane reeds of the clarinet or saxophone can be unambiguously classified as being 'inward-striking' (they close in response to an increase in static pressure at the input) it has not yet been possible to classify the *lip-reed* of the brass instruments in the same manner [Yoshikawa, 1995; Chen and Weinreich, 1996; Newton *et al.*, 2008].

In the 1940s Martin [1942] used a stroboscopic technique to photograph the motion of the lips of a cornet player. This pioneering work has since inspired many other attempts to photograph and film the motion of the lips of brass players during performance [Copley and Strong, 1996; Richards, 2003; Bromage, 2007]. These experiments have been very successful in helping to understand the behaviour of the lip-reed. However, experimenting *in vivo* is not without its difficulties and so a number of researchers have followed the lead of Gilbert and Petiot [1997] in the development of artificial mouths for the sounding of brass instruments [Gilbert *et al.*, 1998; Vergez, 2000; Neal *et al.*, 2001; Bromage *et al.*, 2003; Petiot *et al.*, 2003; Newton, 2008].

Over the last thirty years, computational simulations and physical modelling of the brass wind instrument have run in parallel with experimental research, with experimentation providing physical parameters and constraints as well as confirmation of the accuracy of simulations. In turn, simulations and models of the system have suggested many avenues for renewed experimental research. The first detailed model of the lips of the brass musician is normally credited to Backus and Hundley [1971]. This work was developed further by Elliot and Bowsher [1982] and there have since been many more models and simulations [Caussé *et al.*, 1984; Saneyoshi *et al.*, 1987; Dietz and Amir, 1995; Adachi and Sato, 1996; Msallam *et al.*, 2000; Richards, 2003] to name but a few.

The question remains as to *why* it is important to develop a well grounded understanding of the brass wind instruments. There is, of course, the scientist's natural desire to investigate the unknown, but perhaps more importantly there is also the potential to assist musicians and instrument makers with greater insight than we have at present. The differences between an excellent instrument and an average—or even poor—instrument may be very slight. If we are able to complete our understanding of exactly how the brass family functions then perhaps it will be possible to advise manufacturers as to how a design may be improved [Braden, 2006]. It may even be possible to use a physical model to 'hear' an instrument before it has been built. The aim must not be to replace the skilled craftsman, however, but instead to give him every possible tool.

However, it is not only the future of brass instrument design to which we look. Musicians and historians alike are interested in both preserving and recreating the past. Many believe that music should be performed on the instruments for which it was written—which, after many hundreds of years, may not have survived in working condition, if at all. The careful application of science may allow us to determine what an instrument may have sounded like, even if the surviving instrument examples are too fragile to be played. An understanding of the underlying acoustics will allow us to objectively classify the brass wind instruments [Myers, 1998].

1.1 Aims

The aims of this thesis are:

1. To measure and compare the lip opening area of the lips of the brass wind musician as a function of time for a variety of different musicians and instruments. Further, to extract information pertinent for the development of accurate physical models of the lips.
2. To determine whether or not a constriction or restraint on the motion of the lips at the loudest levels can be responsible for the distinctive 'brassy' timbre of brass instruments.
3. To investigate the motion of the lips in terms of their motion in the direction of the airflow into the instrument with the aim of further understanding the motion of the lips at varying dynamic level and pitch.
4. To compare the behaviour of the lips during the starting transient for human players on a variety of instruments and to modify an artificial mouth to reproduce this behaviour.
5. To design an experimental procedure for analysing the behaviour of the lip-instrument system during both a lip-slur and a valve-slur.

1.2 Contents

Chapter 2 contains a brief overview of the theoretical background required to justify and understand the work carried out through the rest of the thesis. In particular, the role of the lips of the musician as a pressure control valve and the lip-instrument interaction are examined. One of the main aims of experimental research in this area is to facilitate computational simulation and physical modelling of brass wind instruments. With this in mind, some basic physical models of the lips are discussed.

Chapter 3 presents the main experimental apparatus and methods used to quantitatively measure the motion of the lips of brass musicians throughout the thesis. The concept of an artificial mouth is introduced, and some measurements of the relationship between the lip opening area, height, and width of both human musicians and the artificial mouth are presented.

The sound of a brass instrument changes dramatically and distinctively at the loudest playing levels. Chapter 4 begins with an examination and explanation of some of the mechanisms which have been proposed as a means by which this 'brassy' timbre is generated. One possibility is that the lips of the musician become constrained or restricted in some way during playing at the loudest dynamic. An experiment designed to test whether or not the lip opening area changes as a function of amplitude is described. The data obtained allows comparison of the lip opening area, mouthpiece pressure and radiated sound for a variety of instruments at a number of differing dynamic levels. The second section of this chapter details an attempt to investigate the motion of the lips in the direction of the air flow. The design and manufacture of a new mouthpiece with side window is described. Using this mouthpiece it was possible to use a high speed camera to film the 'three-dimensional' motion of the lips of several different trombonists at the loudest dynamic levels, as well as at more 'normal' volumes.

Chapter 5 contains an experimental investigation into the behaviour of the lip-instrument system during the starting transient. The transient is an important feature of brass instruments for two reasons: firstly, the ease with which a player can form a note is used by musicians as an indicator of instrument quality and second, the transient includes tonal information essential to the listener. This chapter examines the behaviour of both lips and instrument over the first 100ms of the start of a note on three different instruments—two trombones and one horn—played by six different musicians. Analysis of variations in amplitude and frequency of the lip opening area during the starting transient is made. Additionally, the same analysis is applied to the transients obtained during both a 'lip-slur' and a 'valve-slur' where the musician changes smoothly from one note to the next.

The starting transient of the artificial mouth was investigated and the results are shown in chapter 6. As part of this section of the work, the pressure in the mouth of human players during the starting transient was also measured and these results are given.

The final chapter, 7, presents the conclusions from this work along with suggestions for further work in this area.

Chapter 2

Lip reed and brass wind instrument acoustics

'Outside of a dog, a book is man's best friend. Inside of a dog it's too dark to read.'

—GROUCHO MARX

There are many textbooks that give a broader description of the acoustic behaviour of lip-reeds and brass-winds than is appropriate for inclusion within a thesis (for example [Benade, 1976; Backus, 1977; Fletcher and Rossing, 1998; Campbell and Greated, 2001]). A detailed overview of experimental and theoretical research in the field was published in Acta Acustica 2004 by Campbell [2004]. This chapter outlines the underlying theory directly relevant to this work.

All of the common Western wind instruments (with the exception of the flute family, which we will not consider here) operate in more or less the same way. The musician places one part of the instrument in the mouth and blows. This causes a *reed* to vibrate, which creates a modulation of the airflow into the instrument. The reed behaviour is partly dependent on the properties of the

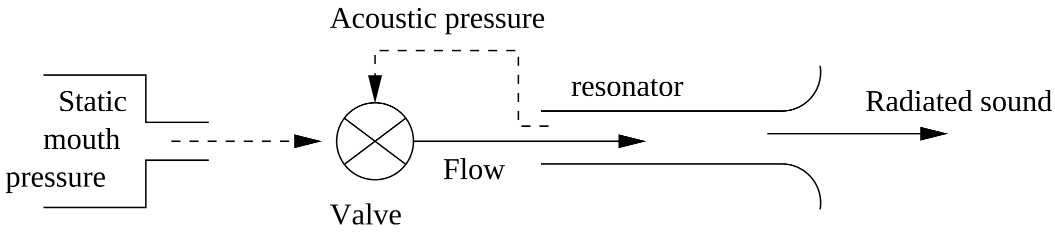

Figure 2.1: *A basic model of a wind instrument. The player creates a static overpressure in the mouth. The pressure difference across the valve causes the valve to oscillate and air to flow into the instrument. The lips receive acoustical feedback from the air column within the resonator and further modulate the input airflow.*

instrument body, which in turn are at least partly dependent on the behaviour of the reed. In instruments like the oboe, clarinet, and bagpipes the reed is typically made of cane.

In the case of brass instruments, however, the reed (or valve) mechanism is formed by the player pressing the lips into the mouthpiece and buzzing them, and so we use the term *lip-reed*. As the player blows, there is a pressure difference created across the lips which causes them to oscillate, creating an acoustic pressure signal at the input to the instrument. The lips receive acoustical feedback from the air column within the instrument, further modulating the airflow. This feedback loop is shown graphically in figure 2.1.

We can thus split our study of brass wind instruments into four parts [Carral, 2006]:

- The behaviour of the resonator—the air column or instrument bore.
- The behaviour of the acoustic generator—the lip reed.
- The coupling between the lip reed and the instrument.
- Any nonlinearities in the system.

We will begin our theoretical treatment of the brass wind instrument with the acoustic behaviour of the resonator—the instrument itself.

2.1 The resonator

Some typical brass wind instruments are shown in figures 2.2 (a modern orchestral trombone), 2.3 (a modern horn) and 2.4 (a natural trumpet). They can vary widely in size and shape, but the vast majority of brass instruments share several common features. Typically, they consist of a cup shaped mouthpiece, a section of tubing with cylindrical and conical sections of approximately circular cross section and a rapidly flaring bell section. In some cases the length of the instrument is fixed (for example, the natural trumpet), and in others the player may alter the length either by the use of *valves* (as in the modern horn) to introduce or remove some sections of tubing or by using a *slide* (for example, the trombone) to change the length of the instrument. Some brass instruments (such as the cornetto) make use of finger holes. However, this is uncommon and no instruments of this type were investigated during this work.

It is interesting to note that in spite of the name not all brass instruments are made of brass, or even metal. In fact, there are several examples where the resonator is made of wood. One highly controversial area of brass instrument acoustics is whether or not the material from which an instrument is made has an effect on the sound [Kausel and Mayer, 2008; Whitehouse and Sharp, 2008; Pyle, 1998; Moore *et al.*, 2005]. In this thesis, however, we do not consider the effect of wall vibrations.

Figure 2.2: *A modern orchestral trombone. The bore is approximately cylindrical (in the first position, approximately 70%). The player can change the length of the instrument by the use of the movable slide section. Image provided by Arnold Myers [Myers, 2009]*

Figure 2.3: *A typical modern horn. The instrument has several conical sections. The player can change the length of the instrument by using the valves to add or remove sections of tubing. Image provided by J. Chick [Chick, 2009]*

2.1.1 Pipe acoustics

As a brass player buzzes the lips, air flows into the instrument. The periodic modulation of the air flow by the lip motion leads to the creation of a longitudinal pressure wave which travels along the air column inside the instrument. This wave is partially reflected at any impedance change (see section 2.1.4). If the frequency of the pressure wave is close to one of the resonances of the instrument then a standing wave will be developed within the instrument.

First consider the case of a purely cylindrical instrument. As the lips effectively close the instrument at one end we have to consider the resonant behaviour of a cylinder closed at one end. In this case, our instrument has a

Figure 2.4: *A natural trumpet. The length of the instrument is fixed. Image provided by Arnold Myers [Myers, 2009]*

harmonic series (n=1,2,3...) whose resonances are given by:

$$F_n = c\frac{2n-1}{4L} \qquad n = 1, 2, 3, ... \tag{2.1}$$

where c is the speed of sound in air and we are considering an instrument of effective length L. We note that these frequencies are in the ratio 1:3:5:7, etc and as such our basic instrument would only be able to play the so-called 'odd' harmonics. An instrument of this type would be of fairly limited musical use. In addition, it would also sound 'muffled' or 'subdued' [Backus, 1977]. This is because the cylinder does not radiate sound effectively. Clearly, our basic cylinder is not ready to be used as an instrument. Real brass instruments, however, have a much more complicated shape—they have a rapidly flaring bell and a mouthpiece. How do these change the acoustic properties of the resonator?

2.1.2 The bell

The effect of the bell was discussed in great detail by Benade and Jansson in their two *Acustica* papers from 1974 [Benade and Jansson, 1974; Jansson and Benade, 1974]. They make extensive use of the Webster equation, which describes wave propagation along a tube of varying cross-section, $S(x)$:

$$\frac{1}{S}\frac{\partial}{\partial x}\left(S\frac{\partial p}{\partial x}\right) = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \tag{2.2}$$

with c the speed of sound in air and p representing pressure. The flaring section of the bell reflects low-frequency waves sooner than high-frequency waves [Fletcher, 1999]. Benade and Jansson go on to define the 'horn function':

$$F = \frac{1}{r}\frac{d^2 r}{dx^2} \tag{2.3}$$

where the horn radius at position x is given the symbol r. If we approximate the wavefront as being spherical, then waves with wavenumber $k = \omega/c$ are reflected where $F = k^2$ [Fletcher, 1999]. The horn function F has a maximum value, F^{max} and waves with ω larger than $c\sqrt{F^{max}}$ will be transmitted without hindrance.

In effect, the lowest frequency modes—with the longest wavelengths—cannot 'see' the bell [Campbell and Greated, 2001] as its radius is smaller than their wavelength. Accordingly, for the lower modes the instrument is effectively shorter, raising the frequency of the lower modes. The bell also acts as a high pass filter and improves the radiation of the higher frequency components, giving brass instruments their distinctive sound. This also has the effect of making the sound of brass instruments highly directional—the high frequency components of the sound are most efficiently radiated in the direction in which the bell faces.

2.1.3 The mouthpiece

A typical horn mouthpiece is shown in figure 2.5. The mouthpiece consists of a cup into which the player places their lips and connects to a tapered tube called the shank. At the mouthpiece end, the shank has a radius much smaller than the bore of the instrument. At the instrument end, the radius of the shank is approximately equal to that of the instrument bore so that there is a smooth join between the two. The shape of the mouthpiece means that it effectively acts as a Helmholtz resonator [Campbell and Greated, 2001]. This resonator has a dual effect; it strengthens some of the resonances of the instrument [Benade, 1976] as well as reducing the frequencies of the higher modes of the instrument [Backus, 1977].

Figure 2.5: *A typical horn mouthpiece. The player pushes the lips against the rim and into the cup. The back bore is normally tapered*

So, the bell acts to raise the frequency of the lower modes whereas the mouthpiece lowers the frequency of the higher modes. In this way, the combined effect of instrument body, bell, and mouthpiece serves to create an instrument whose resonances are very close to a complete harmonic series. The exception to this is the pedal note of the instrument (the lowest playable note), which exhibits some very interesting behaviour. The frequency of the pedal note corresponds not to an impedance peak, but instead lies approximately a perfect fifth higher [Gilbert and Aumond, 2008] than the frequency of the lowest impedance peak.

2.1.4 Impedance

One of the most useful definitions we can make when describing the acoustics of brass wind instruments is the specific acoustic impedance, which is normally denoted with a z. The specific acoustic impedance is a function of frequency, ω, and is defined in the following way:

$$z(\omega) = \frac{p(\omega)}{u(\omega)} \tag{2.4}$$

where $p(\omega)$ is the acoustic pressure and $u(\omega)$ is the acoustic particle velocity.

We will make more use of the acoustic impedance, $Z(\omega)$ which is defined as the ratio of specific acoustic impedance to cross sectional area, S, so that

$$Z(\omega) = \frac{p(\omega)}{u(\omega)S} = \frac{p(\omega)}{U(\omega)} \tag{2.5}$$

where we have defined the acoustic volume flow $U(\omega) = u(\omega)S$.

A typical measurement of the input impedance of a brass instrument is shown in figure 2.6. Each resonance of the air column within the instrument corresponds to a peak in the impedance plot [Fletcher and Rossing, 1998]. The possible playing frequencies of the instrument are, as a general rule, very close to these resonances. As such, measuring the input impedance of an instrument allows us to measure the frequencies at which the instrument will sound.

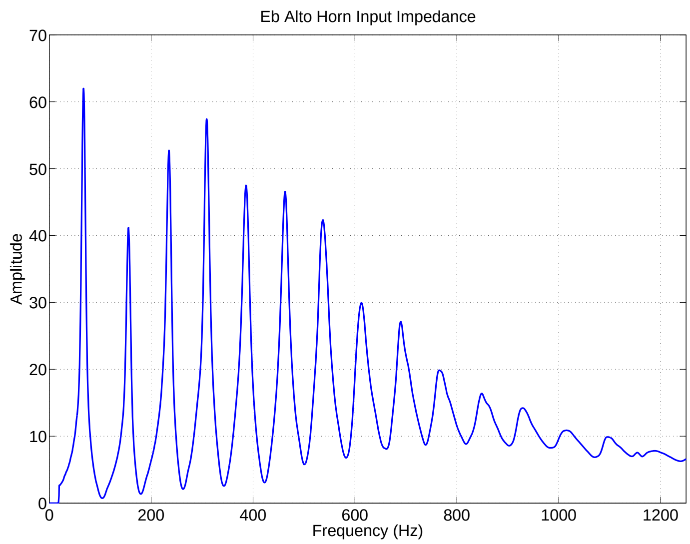

Figure 2.6: *Typical input impedance of a brass instrument. This example is an E♭ alto horn.*

Backus and Hundley [1971] showed that it was the relationship between the input impedance of the instrument and time-varying impedance of the player's lip opening that is primarily responsible for harmonic generation in the trumpet (and by extension the other brass-winds). For further details, see section 2.3.1.

2.2 The lip reed

2.2.1 Inward and outward striking reeds

We can think of a musical reed as a valve that is controlled by the pressure that is generated across it. In wind instruments, the player typically places the mouthpiece of the instrument in the mouth (or on the lips) and blows, creating a static overpressure upstream of the reed. This creates a pressure difference across the valve. In order to precisely describe the physics of the reed it is necessary to describe its response to an increase in air pressure. There are four possibilities: increasing pressure at the inlet to the valve either causes it to open or shut, and similarly at the outlet.

Fletcher and Rossing [1998] use a (σ_1, σ_2) notation to classify reeds into their various types, as shown in figure 2.7. σ_1 has classification $+1$ if a pressure excess p_0 at the inlet tends to open the valve, and -1 if it closes it. σ_2, similarly, refers to the effect of a pressure p applied to the outlet. Helmholtz [1877] was the first to attempt to classify musical valves into different types. He called the $(-1, +1)$ valve 'inward-striking' and the $(+1, -1)$ 'outward-striking'. $(+1, +1)$ has come to be described as either 'sideways-striking' or 'sliding-door'. The combination $(-1, -1)$ does not appear to have any musical use.

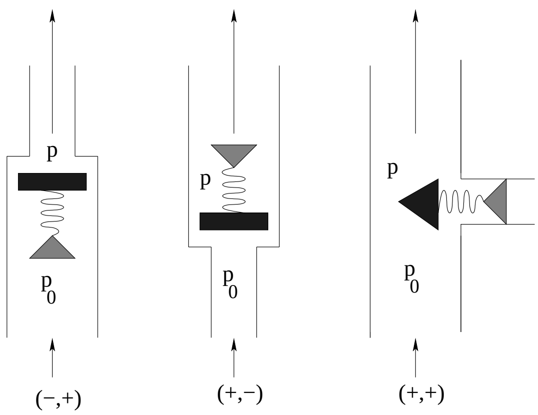

Figure 2.7: *From the left: Inward Striking, Outward Striking, and Sideways-Striking reeds. Adapted from [Fletcher and Rossing, 1998]*

In woodwind instruments such as the saxophone or clarinet the sound is generated by a periodic vibration of a cane reed in the mouthpiece of the instrument. These instruments are well described by simple one-mass models (for example [Bilbao, 2008; Dalmont *et al.*, 1995; Dalmont *et al.*, 2003]) where the reed is represented as a mass on a spring. These single reeds have been unambiguously been classified as inward-striking.

We now move on to the specific case of brass instruments.

2.2.2 The lips as a pressure control valve

In brass instruments the sound is generated not by the vibration of a piece of stiff cane or plastic but instead by a buzzing of the lips of the musician (hence the term lip reed). The lips present a difficult challenge to the theorist; their geometry is not easy to describe and the player is able to greatly vary their mechanical properties during performance. Observing the motion of the lips during playing (see, for example, [Copley and Strong, 1996; Stevenson *et al.*, 2009b] or section 4.7) it is clear that the lips oscillate in all three dimensions.

It has not yet been possible to definitively classify the lip reed as either inward or outward striking. In fact, the lips seem to display properties of being both inward *and* outward striking [Newton *et al.*, 2008; Chen and Weinreich, 1996; Cullen *et al.*, 2000]. This ambiguity makes it impossible to describe the physics of the lip reed using only a model with only a single degree of freedom.

However, despite the apparent difficulties in modelling the lip reed there have still been some very successful attempts to do so. These studies generally approximate the lip reed to be predominantly 'outward-striking'. Some of the most successful projects are those of Adachi and Sato [1996], Vergez and Rodet [2000] and Msallam *et. al* [2000].

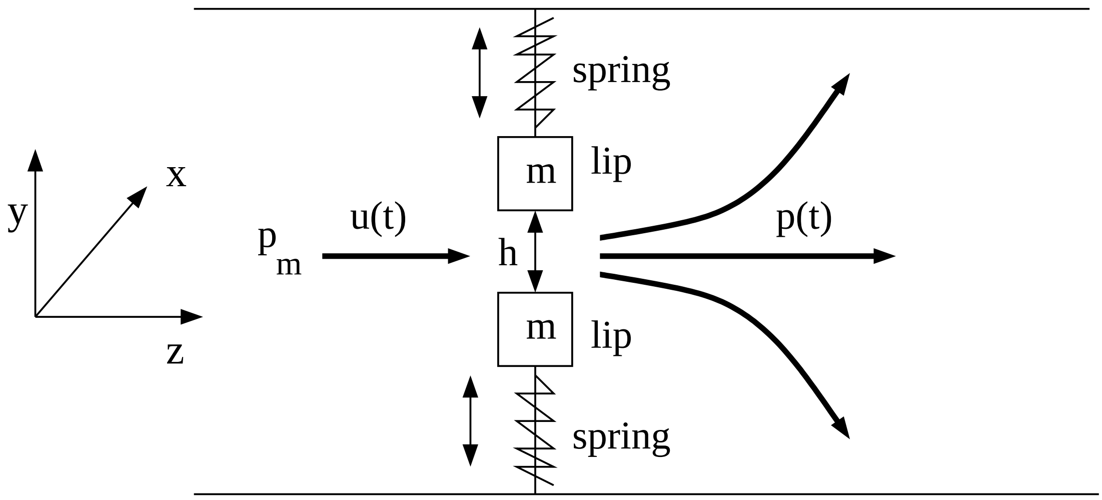

Figure 2.8: *A basic one mass model of the lip reed. The lips are assumed to behave like masses on springs. A constant pressure P_m is applied in the mouth and a volume flow u enters the lip channel, whose height is denoted by h. The downstream pressure is simply denoted p*

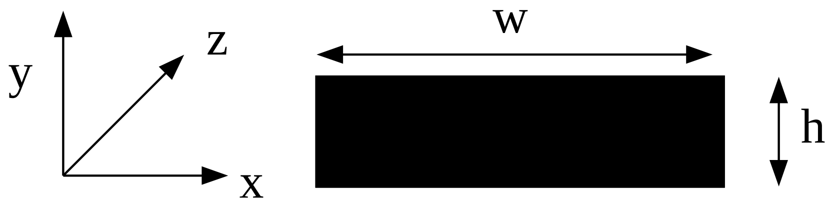

Figure 2.9: *The lip opening area of a one mass model (as in figure 2.8). The height of lip opening is again labelled h and the width of the channel is w. In some models, w is kept fixed*

2.2.3 A basic model of the lips

Elliot and Bowsher [1982] were among the first to formulate a satisfactory model for the lip reed. A basic diagram of this model is shown in figure 2.8. They assumed that the pressure in the mouth was constant, that any flow in the lip channel could be described using the Bernoulli equation and that there was no pressure recovery downstream of the lips. Under these conditions, they showed that the volume flow across the lips, U, may be written in the following form:

$$U = \sqrt{\frac{2\Delta P}{\rho}} A \tag{2.6}$$

where the pressure difference across the reed is ΔP, the density of air is ρ and the cross-sectional area of the lip opening is written as A. If we assume the pressure in the mouth (P_m) is constant (the player blows at an approximately constant rate) and include the implied time-dependence [Gilbert *et al.*, 2006]

$$U(t) = A(t)\sqrt{\frac{2(P_m - p(t))}{\rho}} \tag{2.7}$$

then it becomes clear that the behaviour of the lip opening area as a function of time has a direct bearing on the volume flow entering the instrument. The opening area for the model in question is shown in figure 2.9.

A one-dimensional lip model, with angular frequency w_l, mass per unit area of the lips μ_l, lip opening $H(t)$ and quality factor Q_l can be defined in the following way [Gilbert *et al.*, 2006]:

$$\frac{d^2}{dt^2}H(t) + \frac{\omega_l}{Q_l}\frac{d^2}{dt^2}H(t) + {\omega_l}^2 H(t) = \frac{P_m - p(t)}{\mu_l} \tag{2.8}$$

If we then describe the acoustics behaviour of the instrument in terms of the input impedance

$$P(j\omega) = Z(j\omega)U(j\omega) \tag{2.9}$$

with the input impedance, mouthpiece pressure, and volume flow into the instrument all treated in the frequency domain, and given symbols Z, P, and U respectively. Combining equations 2.7, 2.8 and 2.9 gives the so-called 'three equation' model of a brass wind instrument [Gilbert *et al.*, 2006].

A basic one degree-of-freedom model has been greatly successful in producing realistic synthesised tones [Adachi and Sato, 1996; Dietz and Amir, 1995; Msallam *et al.*, 2000]. However, there are several features of the lip reed which a one degree of freedom is unable to produce [Yoshikawa, 1995]. In particular, a brass musician is able to 'lip' a note both above *and* below the resonant frequency of the air column [Cullen *et al.*, 2000; Cullen, 2000; Neal *et al.*, 2001; Campbell, 2004]. A four degree of freedom model is required to explain this particular behaviour [Richards, 2003].

2.3 The lip opening area

In order to perform successful computational simulations of the behaviour of the lip reed it is necessary to understand how the lip opening area varies as a function of time. In order to simplify the calculations most models consider not the opening area, but the opening *height*, $H(t)$, of the lips, and assume that the area is a basic function of the height. The most common approach is to model the opening area in the form

$$A(t) \propto H(t)^n \tag{2.10}$$

with $n \geq 1$. For $n = 1$, the width of the lip opening remains constant throughout the motion (the opening area is rectangular, with constant 'width'). This linear relationship was used in early work by Saneyoshi *et al.* [1987].

The $n = 2$ case was used by Msallam *et al.* [2000] to achieve considerably more accurate results than in the simple linear model of Saneyoshi *et al.*. In this quadratic relationship the width of the lip opening increases directly as the height is increased.

Richards [2003] showed that the behaviour of the lip reed lies somewhere between these two cases—that is, $1 < n < 2$. In more recent studies, however, it has been suggested that there may in fact be two values for the exponent n, with each being used at different points in the cycle [Bromage, 2007].

2.3.1 Harmonic generation

The sound produced by brass instruments is complex. The sound heard by the listener consists of many harmonically related frequency components, some of which may have amplitudes larger than that of the fundamental. Backus and Hundley [1971] performed a detailed experimental and theoretical investigation into the physical mechanism behind harmonic generation in the brass wind instruments. There were four main parts to their investigation:

1. Theoretical estimation of the amount of higher harmonic distortion that should be expected within the instrument.
2. Measurement of variation in input impedance with sound pressure level.
3. Measurement of intermodulation distortion.
4. Measurement of output harmonic distortion for different mouthpiece pressures

They found that nonlinear effects did not contribute greatly to harmonic generation, nor did the input impedance vary greatly at different input pressure. They concluded that the main mechanism behind harmonic generation was the relationship between the input impedance of the instrument and the time-varying impedance of the lip opening. When the lip opening is small, the lip impedance is much greater than the input impedance of the instrument for any frequency. As the lips open further, their impedance lowers until it is much smaller than that of the instrument. So, for some part of the cycle, the volume flow into the instrument is controlled by the lips, and for the other part it is controlled by the instrument itself. They used this information to successfully simulate the resultant pressure created in the mouthpiece. It has since been shown that Backus and Hundley underestimated the effect of the nonlinear behaviour of the system [Elliot and Bowsher, 1982; Hirschberg *et al.*, 1996], however, their basic analysis remains sound.

Chapter 3

Quantitatively analysing the motion of the lips

'I'll play it first and tell you what it is later.'

—MILES DAVIS

3.1 Optical techniques for studying the lip-motion

Early studies of the motion of the lip-reed during brass wind instrument performance were conducted using a stroboscope [Copley and Strong, 1996; Martin, 1942]. Stroboscopic technology requires a careful tuning of the strobe frequency relative to the expected fundamental frequency of the lip vibration. However, the stroboscope is unable to capture an entire cycle of lip motion in real time. Assuming that the lip vibrations are uniform we can use aliasing in order to reconstruct the motion of one individual cycle of motion from images captured over several cycles. This means that stroboscopic studies can only be made during the steady state regime of lip oscillation.

Throughout this study a high speed digital camera has been used to capture the motion of the lips. This technique is much simpler than the use of a strobe; no assumptions about the lip motion or frequency need be made because the sampling frequency of the camera is sufficient to capture the motion of the lips directly. The camera used was a Vision Research Inc. Phantom v4.1. This camera is capable of recording at frame rates as high as 10,000 frames per second, depending on the resolution required. Throughout this work, a typical frame rate was 6000 frames per second at an image size of 256x128 pixels.

3.1.1 Transparent mouthpieces

In order to allow the motion of the lips to be captured directly specially designed transparent mouthpieces were used. These mouthpieces have been developed and used over the course of several studies at the University of Edinburgh [Richards, 2003; Bromage, 2007; Newton, 2008] which were in turn based upon a design by Ayers [1998b]. These mouthpieces are designed so that the shank protrudes sideways instead of forwards. This allows an optical glass window to be placed in the plane facing the lips. A photo of the transparent trombone and horn mouthpieces can be seen in figure 3.1. Schematics of the mouthpieces are shown in figure 3.2 and figure 3.3. The horn mouthpiece differs slightly from the trombone mouthpiece in that the rim and optical window are not parallel. This is because during typical playing on the horn the top lip tends to 'overhang' the lower. For this reason, it is necessary to film from an angle slightly 'below' the straight-on position. To facilitate this, the window is angled.

The mouthpieces are designed to be as realistic as possible for the player. With this in mind, the rim dimensions and cup volume are based on commercially available models. The tenor trombone mouthpiece is based on a Denis Wick 6BS whilst the horn mouthpiece has dimensions taken from a Paxman 4C. The internal shape of the transparent mouthpieces differs from that of more traditional mouthpieces, which tend to taper towards the shank. However, large variations in internal cup shape exist between different models of commercial mouthpiece and so it is not expected that the internal shape is a critical factor in producing a playable mouthpiece. Input impedance measurements have shown that the transparent mouthpieces are very similar to the mouthpieces that are available for purchase by brass musicians [Richards, 2003]. Musicians have stated [Bromage, 2007] that these mouthpieces play well, particularly for the lower modes of the instrument.

Figure 3.1: *The transparent mouthpieces for both trombone and horn. Rim dimensions, cup volume and shank were all taken from commercially available models in order to maximise the comfort and realism for the player*

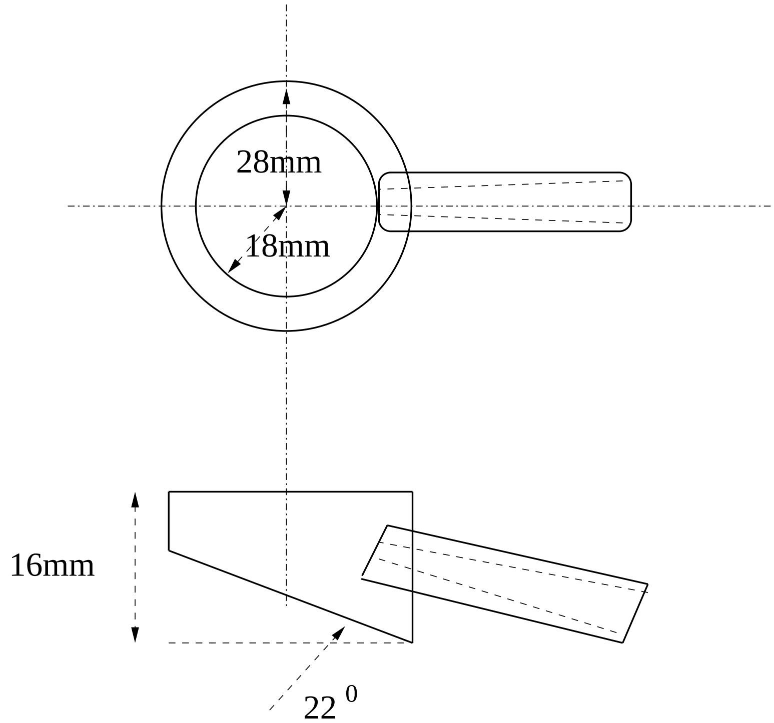

Figure 3.2: *A schematic of the horn mouthpiece. The optical window is angled slightly to allow the lip opening area to be observed when the top lip 'overhangs' the lower*

3.1.2 Fixing the instruments during measurements

It was necessary to clamp the instrument in place during measurements. The high speed camera has a narrow field of focus and so it is important that the area of interest does not move once the camera is in position. Clamping the instrument also ensured that the sound radiated from the bell of the instrument was captured at the same point for each measurement.

The experimental apparatus for the trombone can be seen in figures 3.5 and 3.6. The tenor trombone is, typically, a fairly robust instrument. They are fairly thick walled and have several struts and braces which are hard to damage. This fact, coupled with the geometry of the instrument meant that it was simple to fix the instrument in place using two clamp stands and some

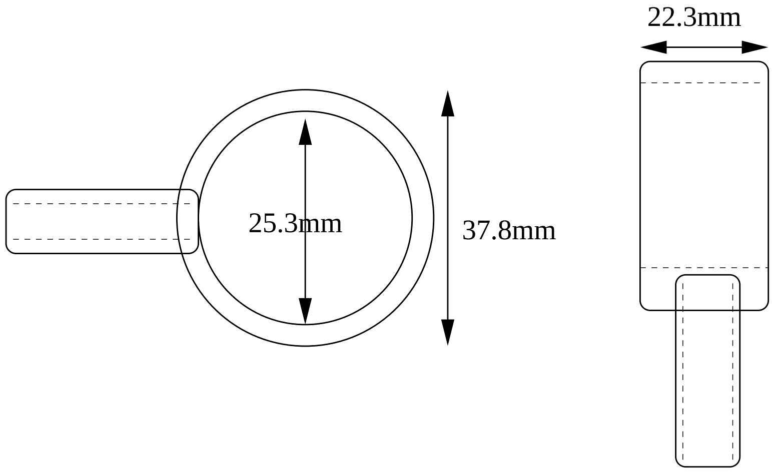

Figure 3.3: *A schematic of the trombone mouthpiece.*

clamps. The instrument was angled slightly so that the nose of the player did not touch the PCB microphone inserted into the mouthpiece. This did not affect the playability of the instrument in any significant way.

The apparatus for the horn can be seen in figure 3.7. As can be seen, this is considerably more involved than that of the trombone. The horn has a complicated geometry, and given the design of the transparent horn mouthpiece (see section 3.1.1) it was necessary to mount the horn 'upside down' as can be seen in the figure. Additionally, horns do not typically have any braces or robust sections and so it was not possible to clamp the horn in position. Instead, it was tightly strapped onto a specially designed scaffold which was further padded to protect the instrument. This setup was both heavy and bulky, and so a more refined version was built for the measurements of both 'brassy' playing (chapter 4) and of the starting transient (chapter 5). This improved apparatus can be seen in figure 3.8. Normally, during performance a horn player places his hand inside the bell. In order to keep the experiment as realistic as possible the musicians were asked to

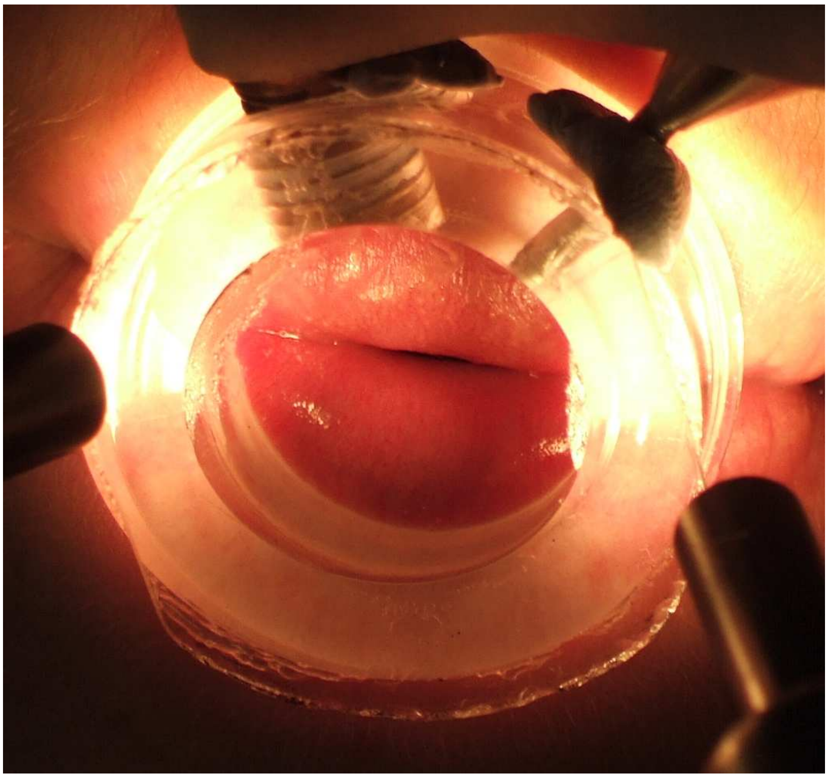

Figure 3.4: *A photo of the transparent horn mouthpiece in use. All of the lip motion can be seen through the transparent window.*

place their hand in the bell even though the instrument was oriented in an unusual manner. Previous studies suggest that musicians are very consistent in where they place their hand [Chick *et al.*, 2004]. The musicians used were confident that the unusual position of the horn did not radically alter the playing characteristics or sound of the instrument.

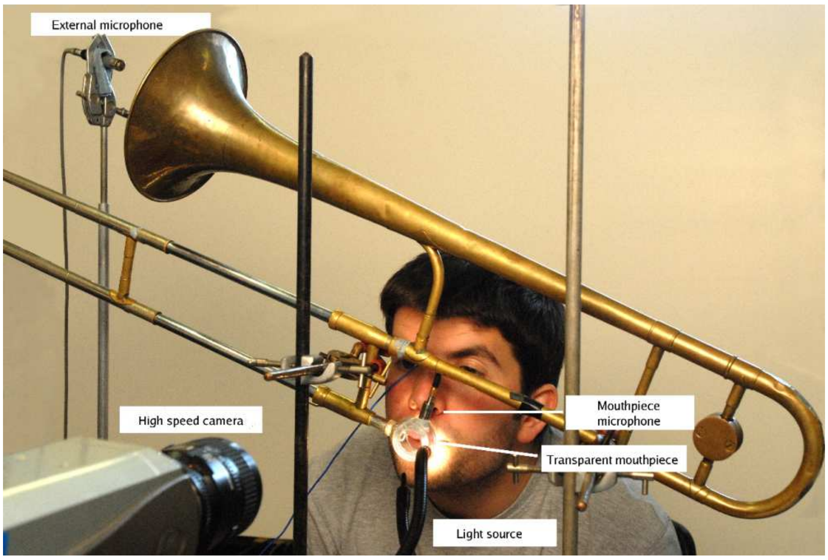

Figure 3.5: *The experimental apparatus for experiments on the trombone. The instrument was fixed in place with two clamps.*

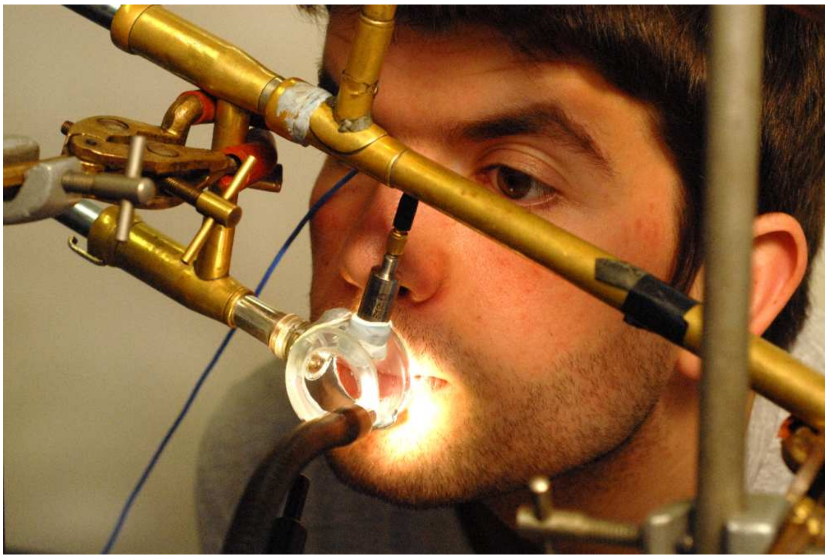

Figure 3.6: *A closeup of the apparatus for experiments on the trombone. The transparent mouthpiece can be clearly seen. The instrument was mounted at a slight angle so that the nose of the player did not interfere with the apparatus. Playability was unaffected*

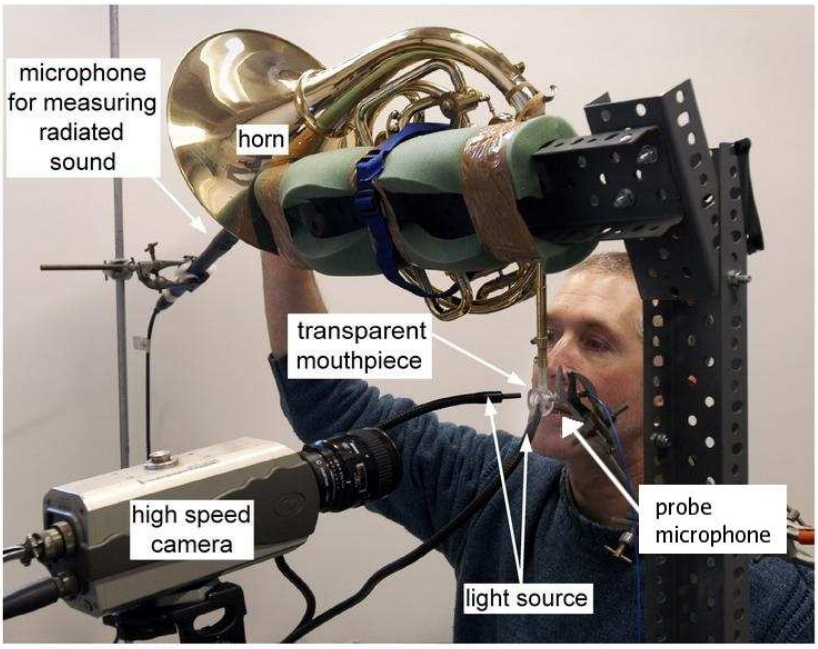

Figure 3.7: *The first horn mounting system. The horn was strapped to a padded scaffold. The instrument had to be mounted 'upside down' because of the shape of the instrument. The high speed camera and light source can also be seen*

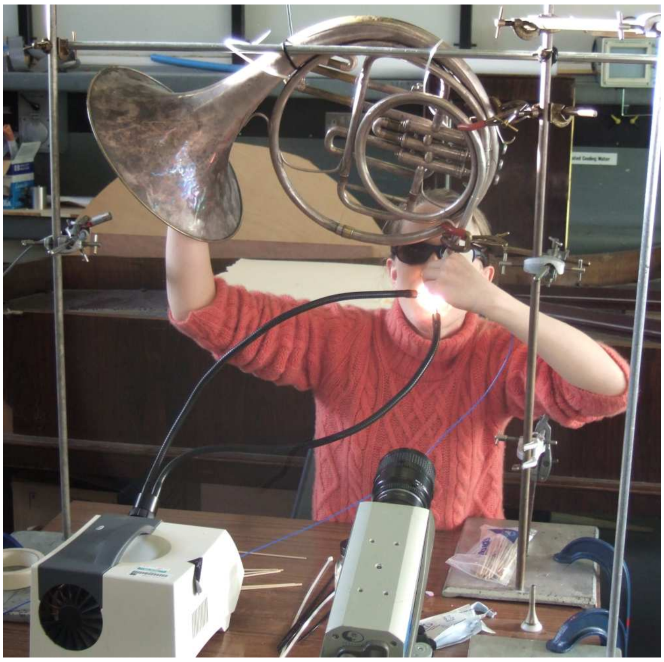

Figure 3.8: *The improved horn mounting system. Three clamp stands were used to support a cross beam. The horn could then be strapped tightly to the cross beam and supported using some soft clamps. This setup was lighter, easier to manipulate, and held the instrument more securely than the first system shown in figure 3.7*

3.2 Analysis method

In order to calculate the opening area of the lips as a function of time, each video that was recorded on the high speed camera was split into a number of sequenced bitmap (*.bmp) images, using the VideoMach software package [www.gromada.com, 2008]. Examples of the images obtained can be seen in figure 3.9.

MATLAB is a high-level language software package for 'algorithm development, data visualisation, data analysis, and numeric computation' [Mathworks, 2008]. The images taken from each video were processed in MATLAB, using a technique developed by Richards [2003] and Bromage [2007]. This technique is repeated here for convenience.

3.2.1 Analysis of the high speed camera footage

The Phantom v.4 camera records in greyscale, and so each still taken from the recordings is also in grey. The first image from the recording is loaded into MATLAB and a threshold grey level is set by the user using a graphical user interface. Each pixel with greyscale level above the threshold is set to white and each below the threshold set to black. This 'binary' process can be seen in figure 3.10. The software displays the 'raw' image on the left and the 'thresholded' image on the right (as in figure 3.10) and the user adjusts the threshold until they are satisfied that only the open area is displayed on the right hand image. If the light level has been set correctly during the recording process then choosing a threshold is straightforward. Bromage [2007] estimated that the error in choosing the threshold was ± 1 pixel, which corresponds to a fraction of a millimetre. These errors are insignificant to the

Figure 3.9: *A complete lip cycle captured using the Phantom v4.1 high speed camera. Note $B\flat_3$, tenor trombone. There are* 22 *successive images in this cycle, with* 11 *in each row. The sequence runs from left to right, top row then bottom. Measurements taken for analysis purposes typically had* 40 *or* 50 *images per cycle*

analysis given here.

If the threshold is set correctly then the black pixels correspond to the opening area of the lips. Once the user has set the threshold level MATLAB counts the number of black pixels and in this way the lip opening area for the image can be deduced. The software then automatically continues the analysis for each image in the data set. This information is concatenated and the time-varying behaviour of the lip opening area found. The software can also be used to find the lip opening 'width' and 'height', by finding the areas of maximum consecutive black pixels in both horizontal and vertical directions. The user can constrain the software to look for the 'height' and 'width' in the appropriate sections of the image (*ie* in the center).

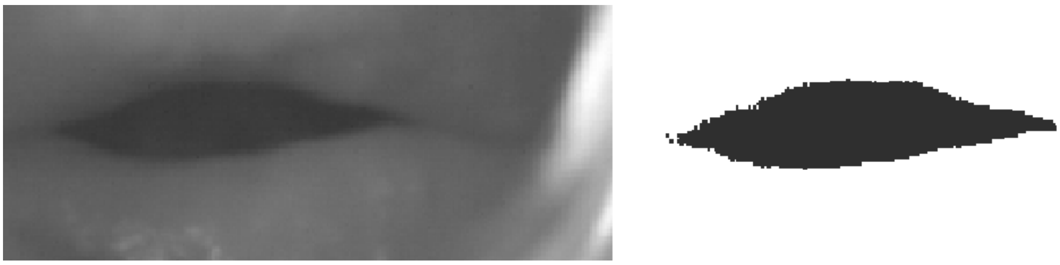

Figure 3.10: *A sample lip image (left), and the corresponding isolated open area (right)*

3.3 Lip open areas

Figures 3.11, 3.12 and 3.13 show three sets of open area data for recordings made by three different horn players of the note F_3 as played on the same instrument. The musicians were asked to play at a *mezzo forte* dynamic. In all three cases, the opening area of the lips changes in an approximately sinusoidal manner. However, the lips remain closed for a significant proportion of the cycle. It is interesting to note that the amplitude of the lip opening area varies

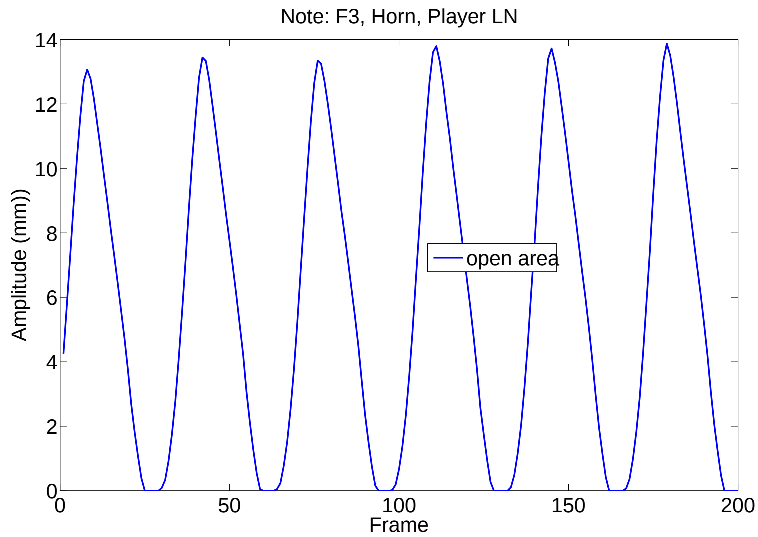

Figure 3.11: *Lip opening area as a function of time. Note F_3, horn. The data was recorded at* 5, 000 *frames per second. Player* ***LN***

only a little from cycle to cycle; the musicians are remarkably consistent in this respect. For players LN and JC the opening area has an amplitude of around 12 to 13mm^2. Player HP, however, has a much smaller amplitude of lip opening area, of approximately 5.5mm^2. The top lip of this player overhangs the bottom more than is usual for a horn musician and this means that the lip opening area that can be observed is correspondingly smaller. Otherwise, however, it is clear that the motion of the lips of player HP do not appear to behave in an anomalous fashion. It should be noted that this measured lip 'opening area' is, in fact, a projection of the opening area onto a plane perpendicular to the lens of the camera. During performance the lips of the musician tend to overlap (as in the case of player HP). For these reasons, we must not assume that what we are able to measure is the 'true' opening area. However, as a tool for extracting quantifiable data about the motion of the lips, this analysis remains extremely

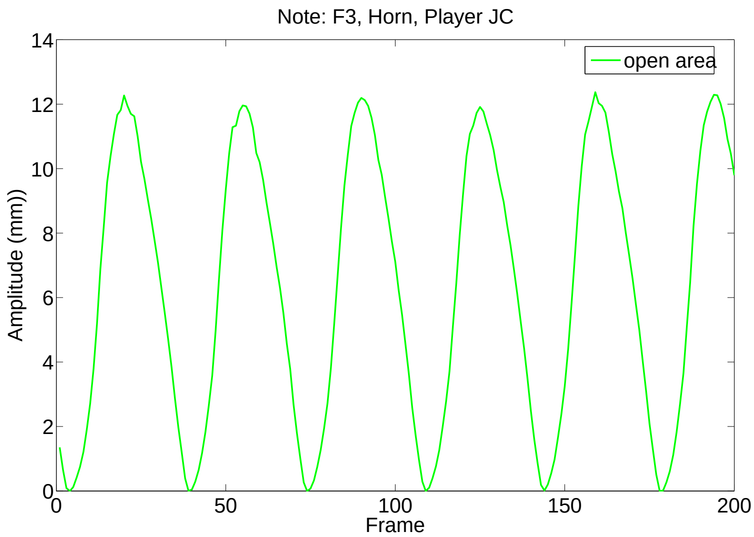

Figure 3.12: *Lip opening area as a function of time. Note F_3, horn. Player **JC***

useful in terms of describing the general behaviour of the lip opening area. With this proviso we shall continue to use the term 'opening area' throughout the present work.

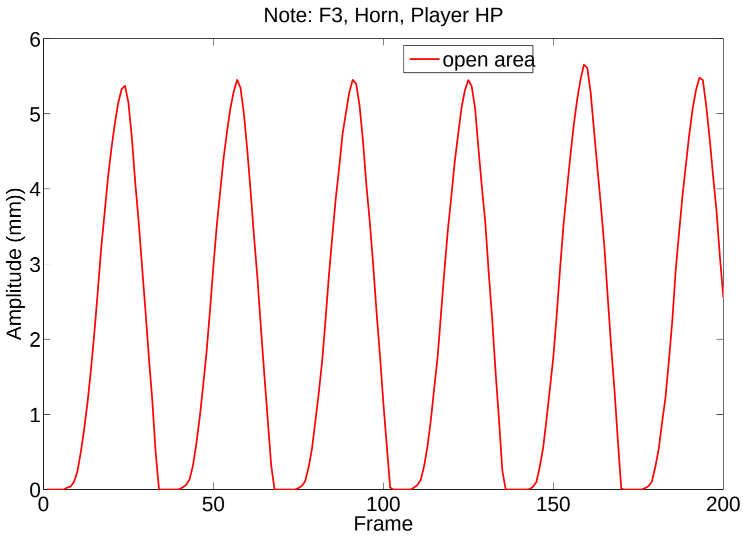

Figure 3.13: *Lip opening area as a function of time. Note F_3, horn. Player* ***HP***

3.4 Evaluating the relationship between lip opening area and lip opening height

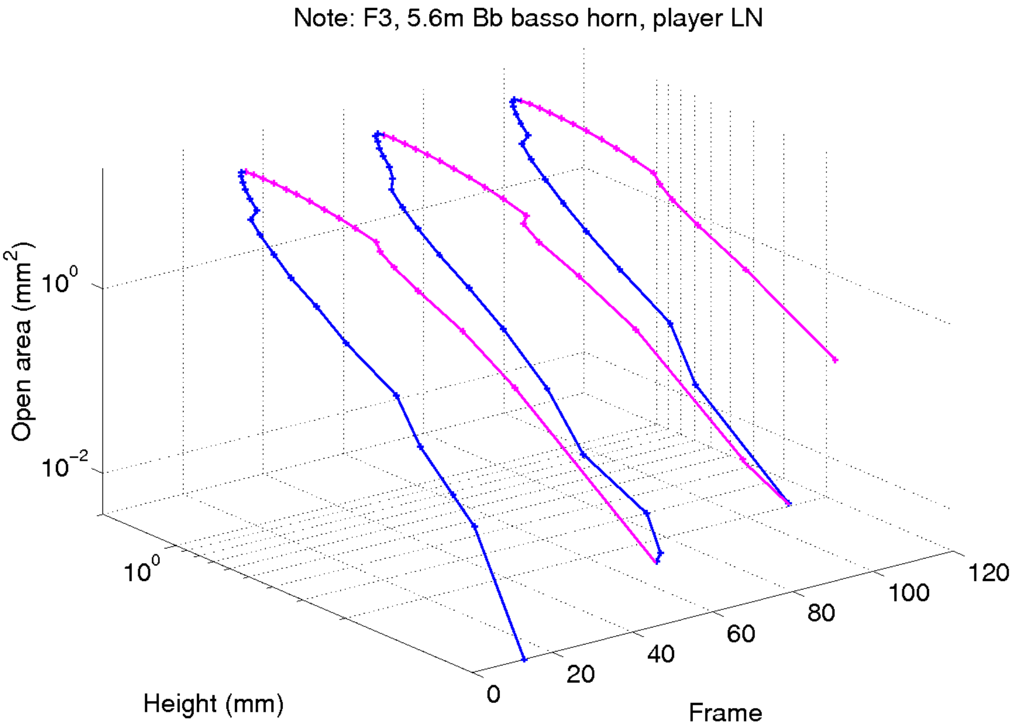

Figure 3.14: *Lip opening area as a function of lip opening height and frame number (time) for three cycles of the note F_3 on the horn. The opening area and opening height are plotted on a logarithmic scale. The opening phase of each cycle is shown in blue, and the closing phase in magenta. Player **LN***

The relationship between the 'height' of the lip opening and the lip opening area is of great interest to those aiming to create physical models of the brass wind instrument, as discussed in section 2.3. Using the MATLAB analysis software the lip opening 'height' can be calculated [Bromage, 2007]. If we assume that the opening area is of the form

$$A(t) \propto H(t)^n \tag{3.1}$$

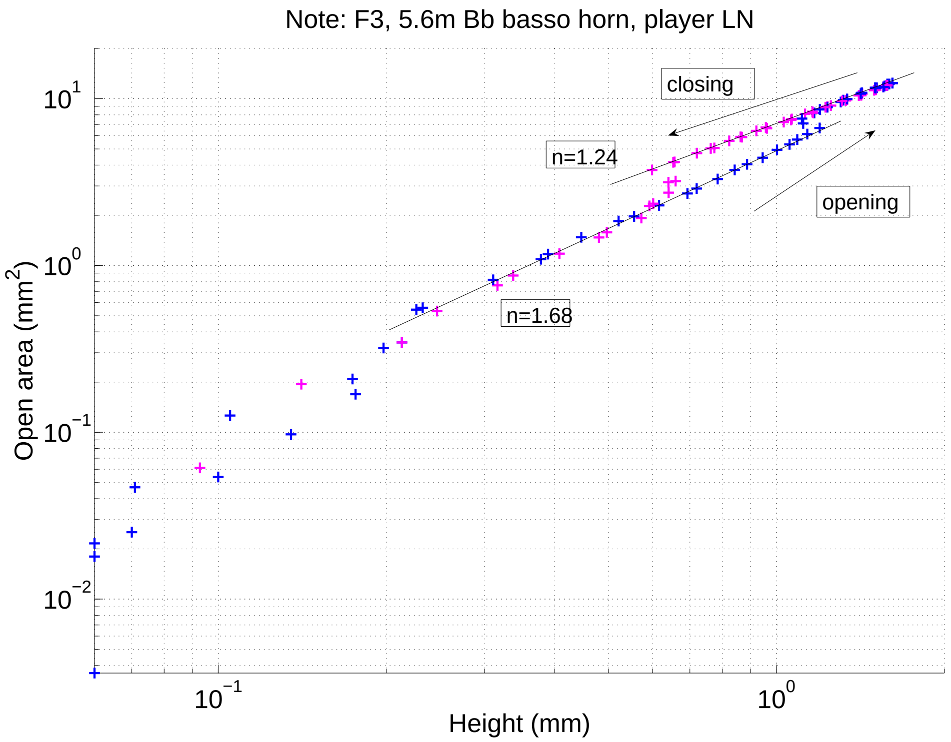

Figure 3.15: *Lip opening area as a function of lip opening height, plotted on a logarithmic scale, for the note F_3 on the horn. These data correspond to the projection of figure 3.14 onto the $y - z$ axis. The opening phase of the motion is shown in blue and the closing phase in magenta. Player* ***LN***

then graphing a plot of this mean lip opening height, $H(t)$, against lip opening area, $A(t)$, on a logarithmic scale should produce a straight line whose gradient is the value of the exponent, n.

Figure 3.14 shows lip opening area as a function of lip opening height and frame number (time) for three cycles of the note F_3 on the horn, as played by player LN, with the opening area and opening height plotted on a logarithmic scale. The opening phase of each cycle is shown in blue, and the closing phase in magenta. It can be seen that the relationship between the lip opening area and the lip opening height is not constant over the whole cycle. Figure 3.15 shows a projection of this data onto the height-area ($y - z$) axis. The

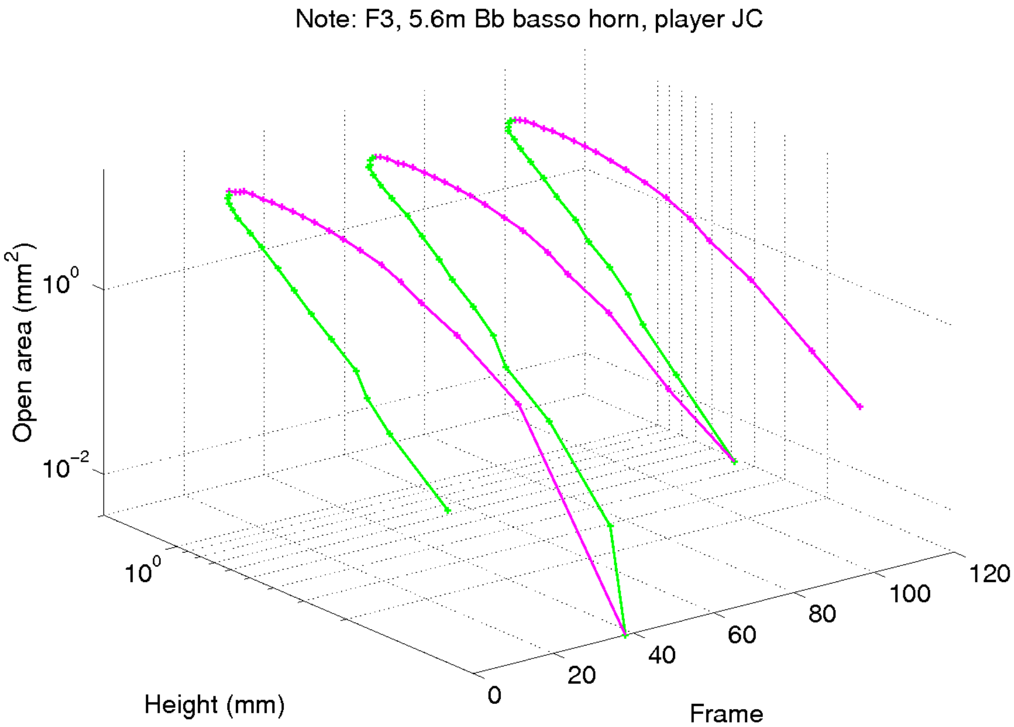

Figure 3.16: *Lip opening area as a function of lip opening height and frame number (time) for three cycles of the note F_3 on the horn. The opening area and opening height are plotted on a logarithmic scale. The opening phase of each cycle is shown in green, and the closing phase in magenta. Player* ***JC***

linear fits shown were performed by eye. This figure simplifies the process of determining the precise nature of the area-height relationship. As the lips open the relationship between the area and the height is approximately constant (*ie* there is a region of constant n). Towards the point of maximum lip opening the behaviour changes from one region of constant gradient to another. As the lips begin to close again, the area-height relationship remains in this second region for a considerable time, before returning back to the first region. In other words, the lips open 'along' a path with gradient $n \approx 1.68$, and then, at the top of the motion, they 'switch' to the region with $n \approx 1.24$ until they reach the point of maximum opening. They then close back along this path, until they

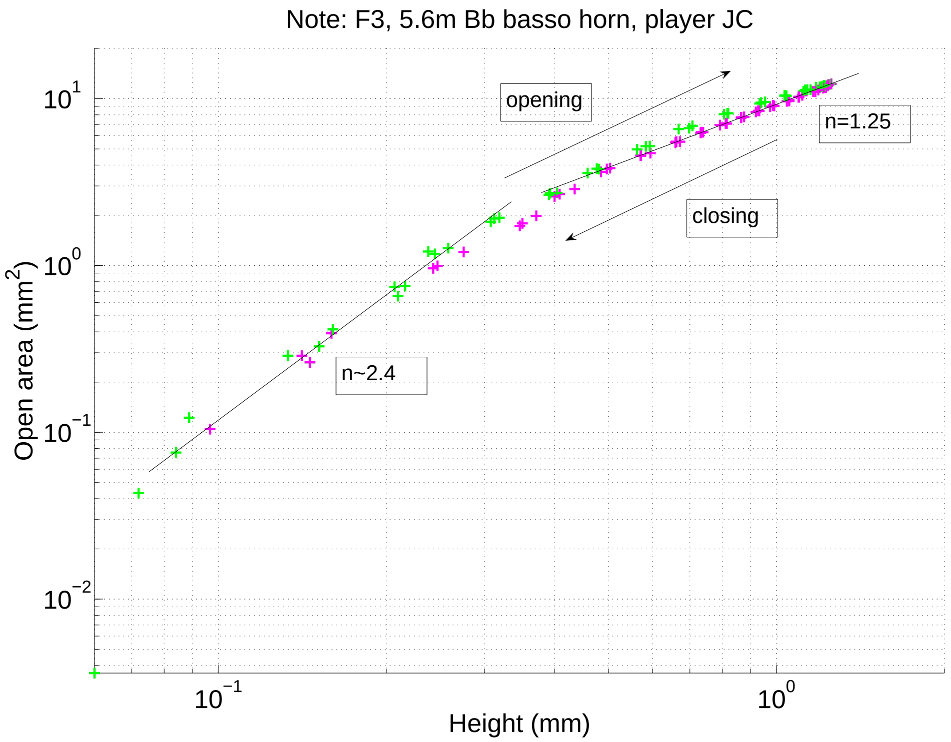

Figure 3.17: *Lip opening area as a function of lip opening height, plotted on a logarithmic scale, for the note F_3 on the horn. These data correspond to the projection of figure 3.16 onto the $y-z$ axis. The opening phase of the motion is shown in green and the closing phase in magenta. Player* ***JC***

switch back to the first region. It is interesting to note that there is a hysteresis effect—the jump between regions occurs at different points in the opening and closing phases of the motion. At the points of smaller opening area the signal to noise ratio becomes poor and as such it is harder to determine any fixed relationships between area and height when the lips are almost closed. However, if one were to try a linear fit for the smaller amplitude data, it would appear that it would have a gradient greater than 1.68.

The lip opening area as a function of lip opening height for the note F_3, as played by player JC on the horn, can be seen in figure 3.16. The projection of this data onto the area-height axis can be seen in figure 3.17. There

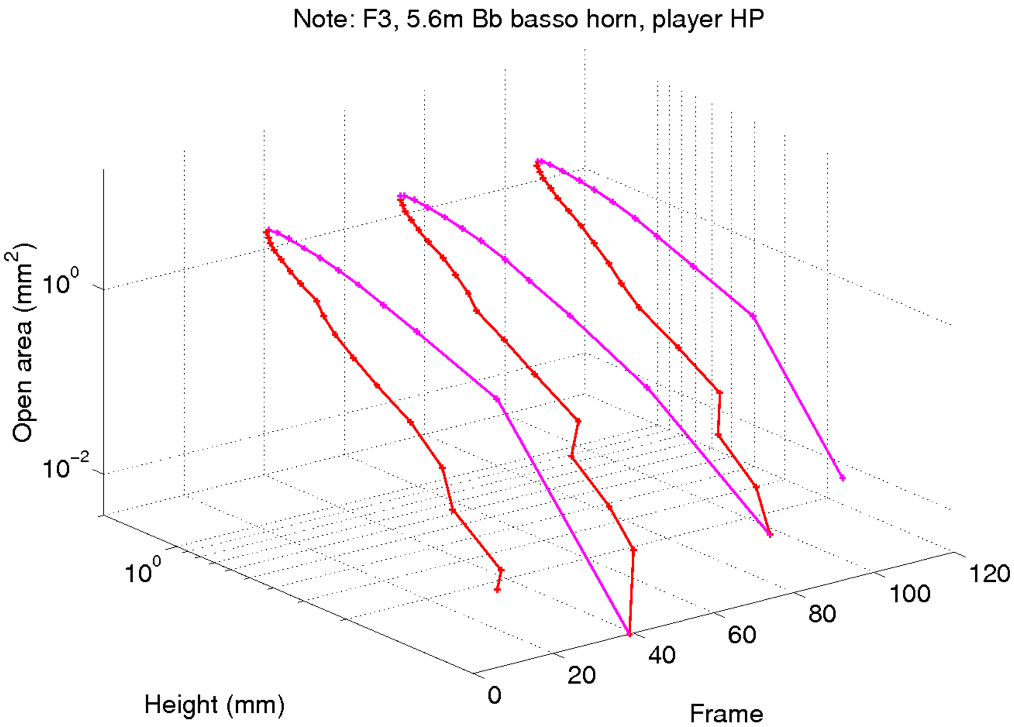

Figure 3.18: *Lip opening area as a function of lip opening height and frame number (time) for three cycles of the note F_3 on the horn. The opening area and opening height are plotted on a logarithmic scale. The opening phase of each cycle is shown in red, and the closing phase in magenta. Player* ***HP***

are some clear similarities to the behaviour of the lips of player LN—the closing phase appears to behave differently to the opening phase, and the relationship between opening area and opening height varies over the course of an individual cycle. Examining the 2-D projection of this data shows that the situation here, however, is not as clear cut as it was in the case of player LN. Towards the point of maximum lip opening it appears that the opening and closing phases follow the same path, along a line with $n \approx 1.25$. However, there appears to be little evidence of the existence of different values of n for the opening and closing phases, and little or no hysteresis effects. For this player it is possible to perform a linear fit for the smaller amplitude data, and

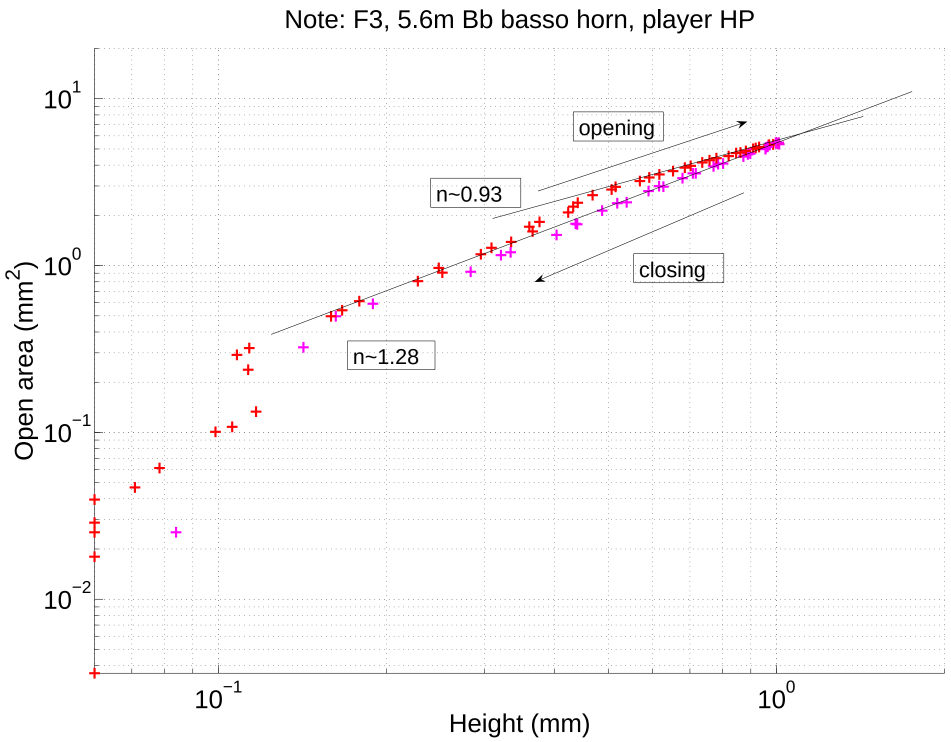

Figure 3.19: *Lip opening area as a function of lip opening height, plotted on a logarithmic scale, for the note F_3 on the horn. These data correspond to the projection of figure 3.18 onto the $y - z$ axis. The opening phase of the motion is shown in red and the closing phase in magenta. Player* ***HP***

in this region $n \approx 2.4$. This is in agreement with the results of Bromage [2007] who found some values for the exponent n with value greater than 2 in the corresponding part of the cycle for trombone players.

Figure 3.18 contains the area-height-time information for the note F_3, player HP, on the horn. Again, the basic shape of the data is consistent with that obtained from players JC and LN. Figure 3.19, the 2-D projection of this data, again shows that in general terms the lips of player HP behave in much the same way as the other two horn players discussed in this part of the study. However, in terms of the specifics of the data there are some subtle differences in the behaviour of the lips of player HP. The lips of this player open firstly 'along' a region of constant n, with $n \approx 1.28$. Towards the middle of the opening phase they switch to a region with $n \approx 0.93$, where they remain until they begin to close again. Until now, no values of $n < 1$ have been observed. Instead of closing along this same region, as in the case of player LN, the lips return to the region of $n \approx 1.28$ as soon as they begin to close, and remain on this region for the entirety of the closing phase.

Player HP is a professional horn player with many years playing experience. However, he has a slightly unorthodox playing technique in which the top lip overhangs the bottom more than is normal for horn players. Perhaps this accounts for the unusual value of the exponent $n \approx 0.93$. In addition, this player was not entirely comfortable with the unusual horn mouthpiece and unorthodox mounting of the instrument. It is therefore difficult to say whether or not this unusual lip behaviour is a true representation of the normal behaviour of the lips of player HP.

In conclusion, the lips of all three musicians behave differently throughout the cycle. The opening and closing phases are not the same, particularly towards the point of maximum lip opening. For each musician it is possible to express the lip opening area in terms of powers of the opening height. The power required appears to vary over the course of an individual cycle. More measurements, on more musicians, are required before firmer conclusions can be drawn.

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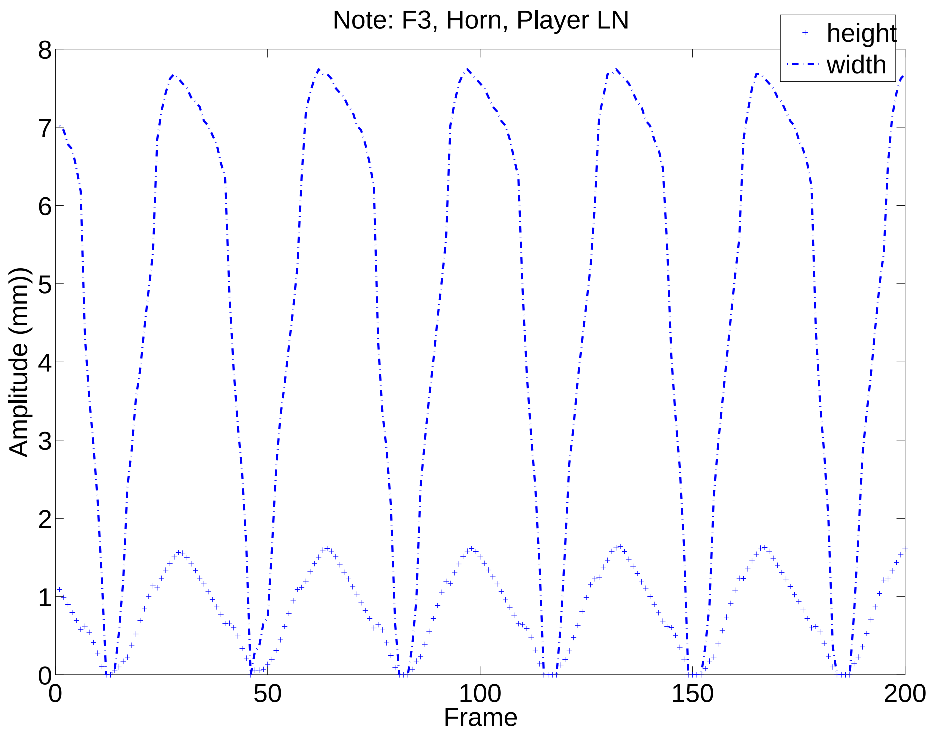


Figure 3.20: *Lip opening height and lip opening width as a function of time. Note F3, horn. Player* ***LN***

3.4.1 Lip opening height and lip opening width as a function of time

Figures 3.20, 3.21 and 3.22 show plots of lip opening height and lip opening width as a function of time. These data correspond to the recordings shown in figures 3.14, 3.16, and 3.18.

Examination of the area-height plots for these data suggested that the motion of the lip was not symmetrical, particularly around the point of maximum lip opening. Examining first of all the height and width data for player LN we see that this hypothesis was accurate, particularly in terms of the behaviour of the width of lip opening. The lip width increases rapidly

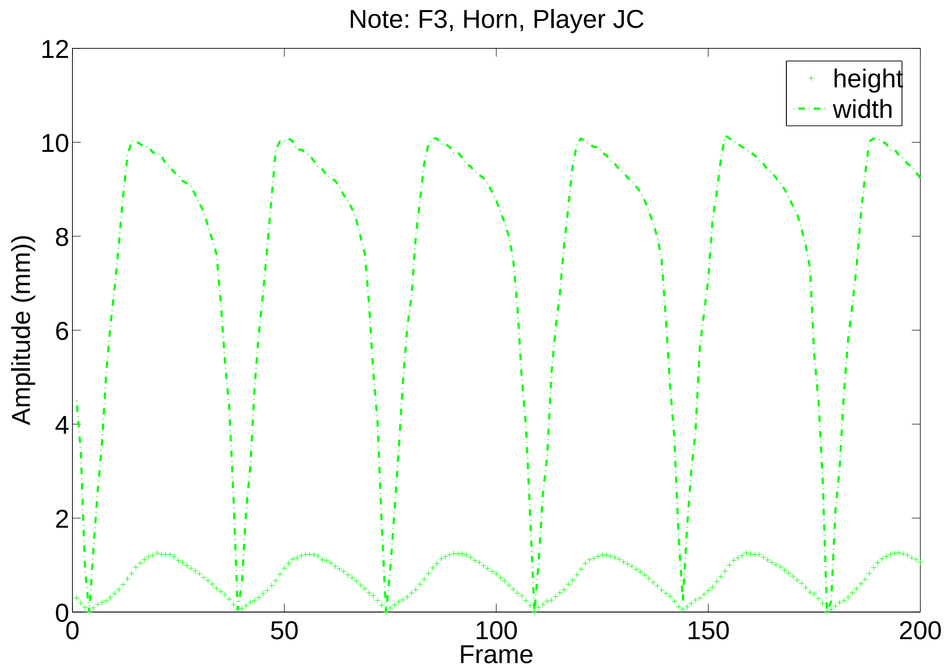


Figure 3.21: *Lip opening height and lip opening width as a function of time. Note F_3, horn. Player **JC***

from zero to its point of maximum opening, and then, when it begins to close, the rate of closing is, initially, much less than the rate of lip opening; clearly asymmetrical behaviour. In terms of the lip opening height, there is less evidence of asymmetry, with the rate of change of opening height being approximately constant during both the opening and closing parts of the cycle.

The lip opening height and width data for player JC is, at first glance, similar to that of player LN, as can be seen in figure 3.21. The opening width increases rapidly until it reaches its maximum value, and then during the closing part of the cycle it decreases slowly before rapidly closing again. The opening height is more symmetrical; with the closing phase being very similar to the opening phase. However, if one compares the amplitudes of the lip opening width and

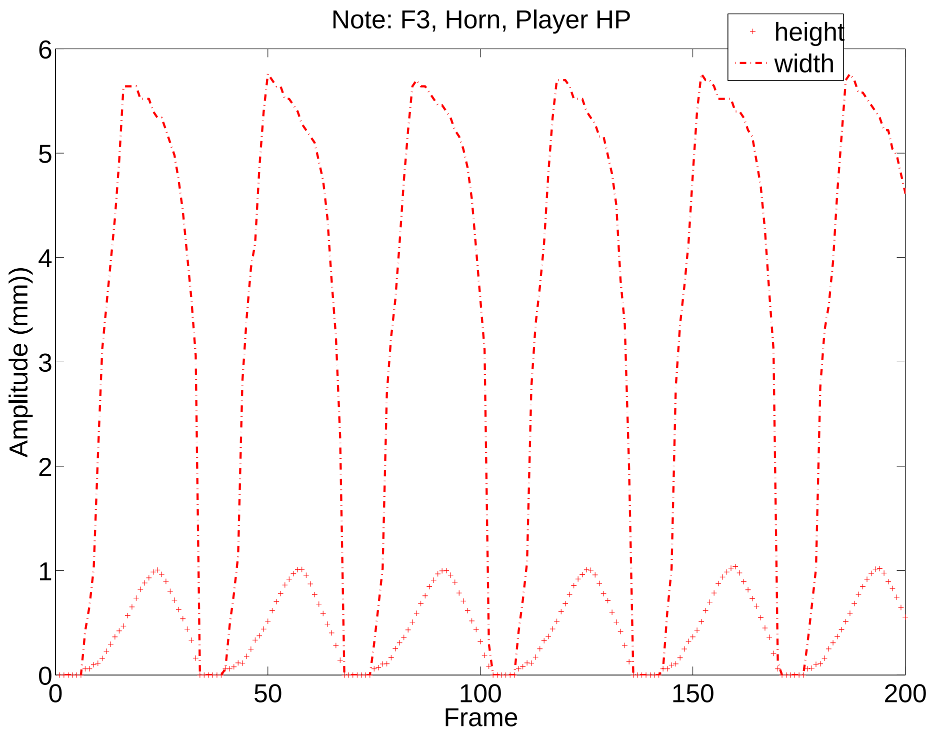


Figure 3.22: *Lip opening height and lip opening width as a function of time. Note F3, horn. Player* ***HP***

height with that of player LN some differences can be seen. In the plots of lip opening *area* in figures 3.11 and 3.12 it was shown that the amplitude of lip opening area was nearly identical for these two recordings by the two different players. However, it can be seen here that there are differences in the width and height of the opening. The width of the embouchure of player JC is wider than that of player LN. In order to make the opening areas approximately equal in maximum amplitude, the maximum opening height of the lips of player LN is therefore larger than that of player JC. It is expected that the most important behaviour is that of the opening area, as it is this which controls the volume flow of air into the mouthpiece. However, it is possible that variations in height as opposed to width may have a small effect upon the sound created. It may be these small variations that make it possible for a player to create a unique and distinctive tone.

Finally, the behaviour of player HP is once more consistent with that of the other two horn players. There is clear asymmetry in the form of the lip opening width, with the closing phase taking longer than the opening phase. The lip opening height is more obviously asymmetrical than in the case of the other two players, with the opening phase taking longer than the closing phase.

In conclusion, the lip opening behaviour of all three horn players is consistent. In each case, when considering the behaviour of the opening height and width, it seems that a small aperture opens in the centre of the lips at the beginning of the cycle, which then rapidly increases in width whilst the opening height steadily increases.

3.5 Experiments using an artificial mouth

There have been many studies of musical instruments using human players, for example [Martin, 1942; Bouhuys, 1969; Yoshikawa, 1995; Ayers, 1998a; Bromage *et al.*, 2006; Fabre *et al.*, 2008; Caussé and Freour, 2008; Amir, 2009]. However, it is desirable for the scientist to maintain as much control on the parameters of the experiment as possible, and this may not be possible using human test subjects. For instance, despite their best efforts it is not reasonable to expect a trumpet player to be able to repeat a note in *exactly* the same way multiple times. The player may make subconscious changes to the embouchure or blowing pressure without being aware of it. Repeatability of a measurement is one of the most desirable features of experimental research in this area [Poirson *et al.*, 2005]. Other than this, there may also be some experimental measurements that are just not practical or possible when using a human musician. For example, there have been some studies that required a controlled change in the mouth cavity of the player [Richards, 2003]. Clearly, one cannot ask a trombonist to decrease the volume of the mouth by exactly 50ml. Other studies [Cullen, 2000; Richards, 2003; Newton *et al.*, 2008] of the lips of brass wind instrument musicians have required a laser diode to be positioned at the back of the player's mouth, *ie* in the throat. No human player could be expected to put up with such an intrusive measurement, and even if it were possible to insert a diode into the throat they could certainly not be expected to play normally.

For these reasons, the development of artificial mouths has been a crucial aspect of research into the performance of brass and woodwind instruments. Whilst there are reports of mechanical devices for the sounding of brass instruments reported as early as the 1940s [Martin, 1941] the first modern artificial mouth for brass instruments is normally credited to Gilbert and Petiot [1997]. Since then, there have been a large number of studies of brass wind instruments using artificial mouths, for example [Vergez and Rodet, 1998; Cullen *et al.*, 2000; Neal, 2002; Petiot *et al.*, 2003; Richards, 2003; Bromage, 2007; Newton, 2008]. Richards [2003] states that the four main advantages for using an artificial mouth instead of human musicians are as follows:

- The artificial mouth can have any number of measuring devices inserted into it; a human mouth cannot.
- A given embouchure will remain approximately constant on an artificial mouth over a long time period, whereas the embouchure of a human cannot be guaranteed constant over more than a single measurement.
- The artificial mouth can blow for as long as the experimentalist desires, with precise control over pressure and flow rate. A human player can only play for a finite time, and cannot control the pressure and flow with such precision.
- The artificial mouth cannot make any unwanted alterations to the embouchure. A human musician may, whether it be conscious or unconscious.

However, despite all the advantages of using an artificial mouth for the study of brass wind instruments, they have not yet entirely replaced human musicians as test subjects. As useful as they are, there are still some features of brass instrument playing that artificial mouths are unable to replicate. They have a limited playing range [Bromage, 2007] and as we shall see in section 4.9 it is hard to achieve an extremely loud playing dynamic using an artificial mouth. One of the aims of this work is to see whether or not the artificial mouth can be used to produce a realistic starting transient. This is discussed in section 6.2.3. However, despite their limitations they remain an incredibly useful tool for the acoustician.

3.5.1 Artificial mouth; design and schematic

Throughout this work, the artificial mouth that was used was that designed by Newton [2008] at the University of Edinburgh. Newton refers to this design as 'replica B'. This model is partly based upon an *in vitro* human vocal fold model developed at the *Institute de la Communication Parlee* in Grenoble, France [Bailly *et al.*, 2006]. A schematic of this artificial mouth can be seen in figure 3.23.

In this design, the 'lips' are formed by stretching latex over an oval shaped cavity, part of the 'lip-block', which can be seen in figure 3.24. Water is then pumped into the latex and the cavity sealed using the water inlet valve. When the lip-blocks are mounted into the mouth the embouchure can be controlled by altering the position of the lip-blocks or by changing the water pressure in the lips themselves. A faceplate cover is mounted on top of the lips so that when an instrument mouthpiece is used there is no direct contact between the lips and the mouthpiece. One of the drawbacks of the artificial mouth used in previous studies at the University of Edinburgh was that the mouthpiece sat directly on the lips, making it difficult to reproduce any particular embouchure [Bromage, 2007]. The cover is designed so that 'Replica B' does not suffer from this problem. However, as noted by Newton [2008], this particular artificial mouth trades adjustability in return for stability. With this artificial mouth, setting up an embouchure is time consuming and once an embouchure has been found it is nearly impossible to alter it without starting once more from the beginning. If the embouchure that is found is not ideal then there is little scope for altering it quickly.

The artificial mouth was attached to an Air Control Industries Ltd 8MS11 0.25kW air pump which was used as the 'lungs' of the artificial mouth. The air pressure supplied to the mouth could be adjusted using a rotary valve. Once an instrument was mounted onto the artificial mouth and the pump started, the pressure in the lips themselves was altered until a playable embouchure was found. At this point, the system was ready for measurement. A photograph of a trombone mounted onto the artificial mouth can be seen in figure 3.25, and figure 3.26 shows a close up of the lips through the transparent trombone mouthpiece.

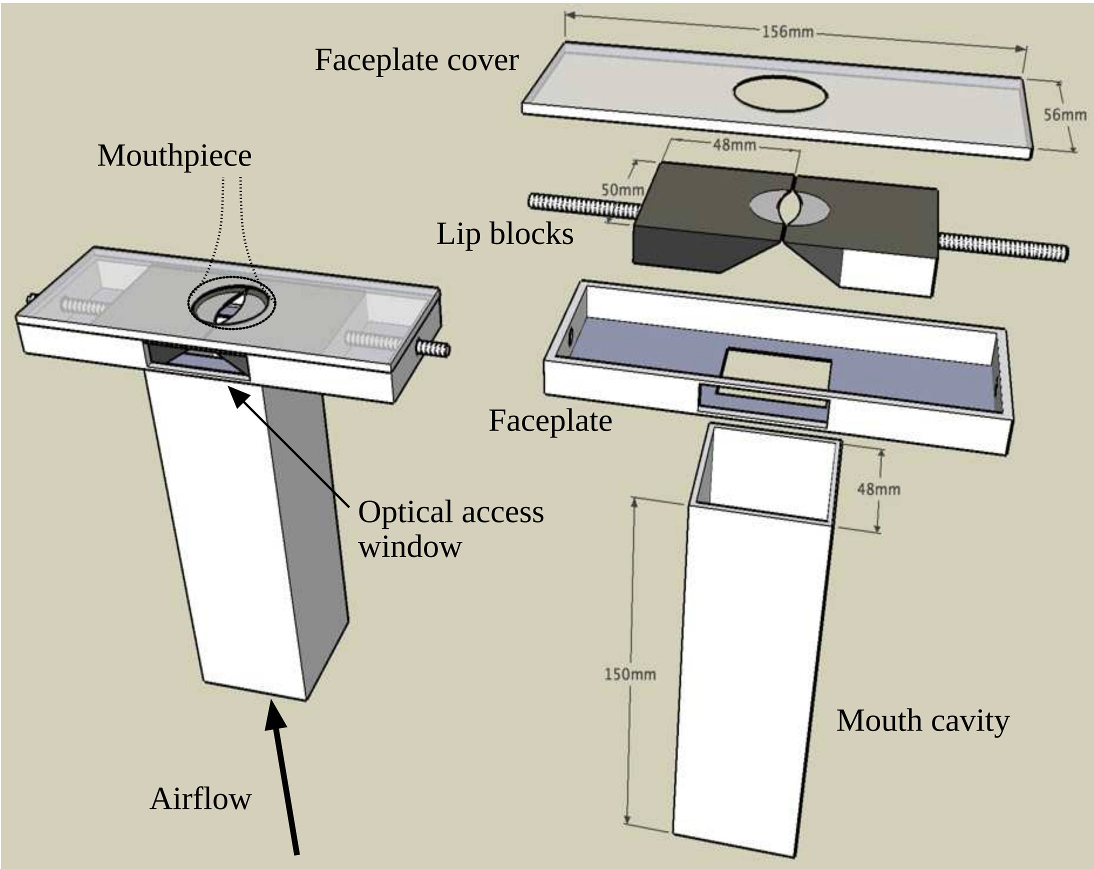


Figure 3.23: *The artificial mouth ('replica B') designed by Newton. The individual elements are shown on the right and the assembled replica shown on the left. From [Newton, 2008]*

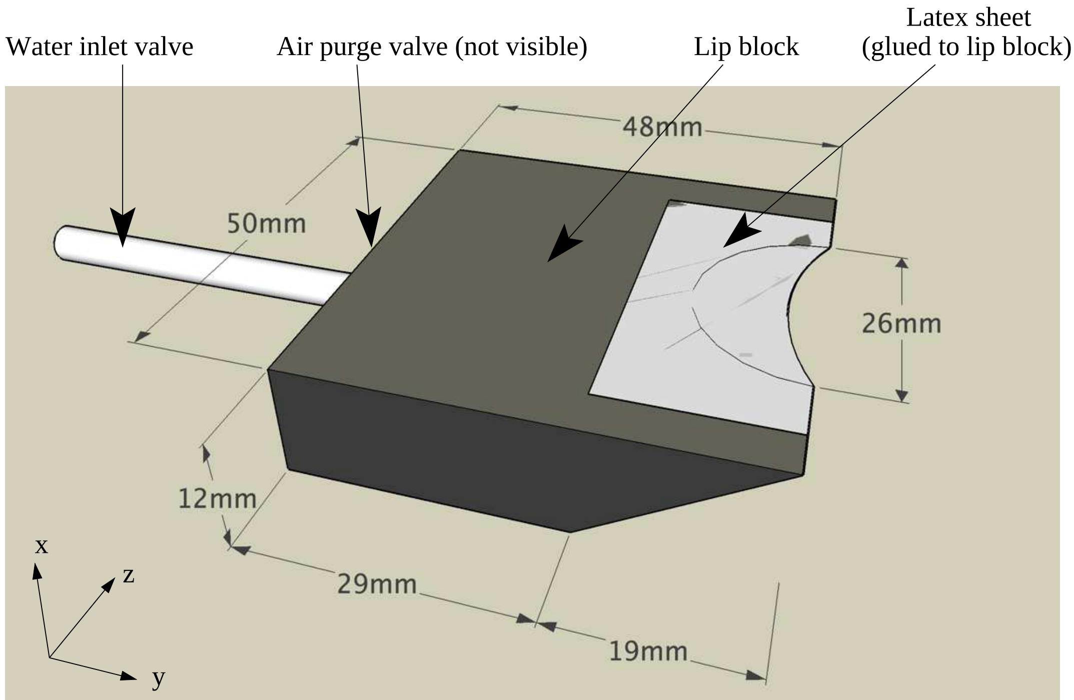


Figure 3.24: *A schematic of the lip block designed by Newton. The lip is formed by stretching latex over a small oval cavity, sealing with superglue. Water is then used to fill the lip using the water inlet and purge valves. From [Newton, 2008]*

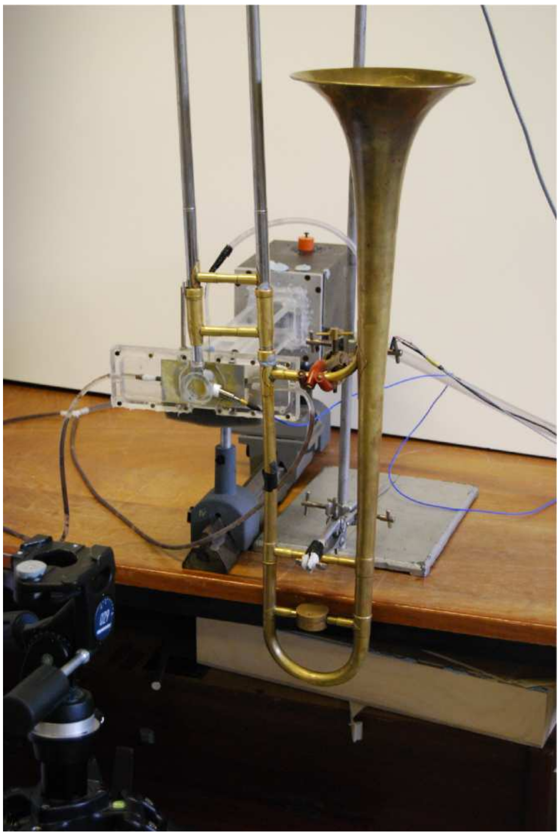


Figure 3.25: *The artificial lips playing the trombone*

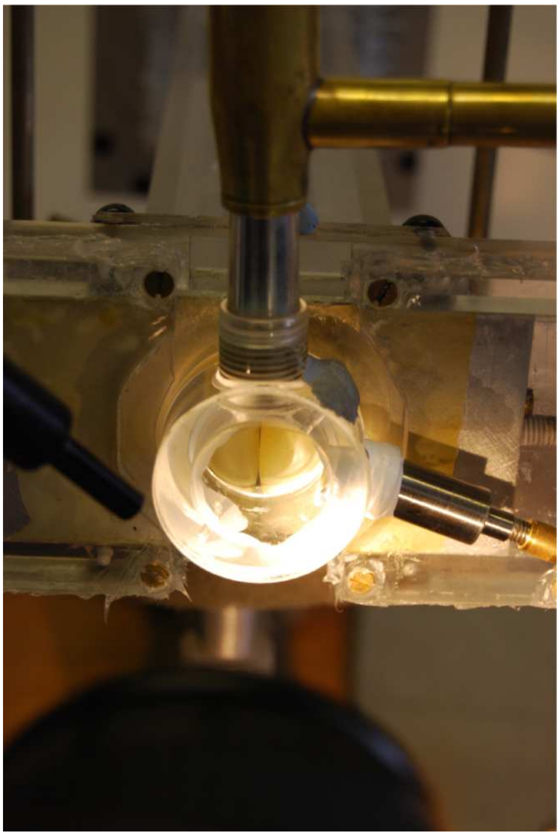


Figure 3.26: *A close up of the artificial lips viewed through the transparent trombone mouthpiece*

3.5.2 Artificial lips: opening areas

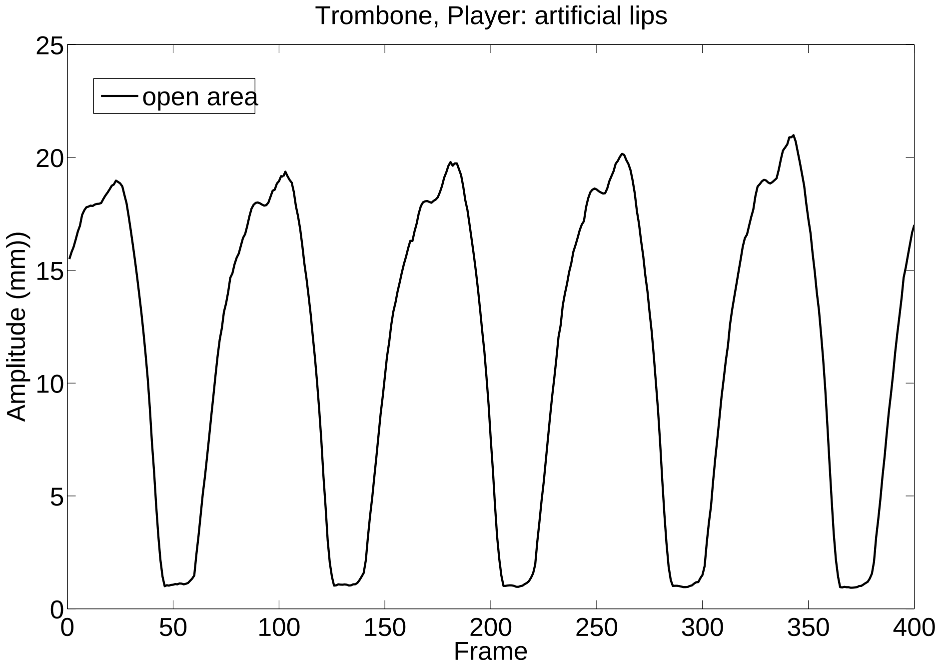


Figure 3.27: *Opening area as a function of time. Note G_2, trombone. Player* ***artificial lips***

Three typical lip opening areas of the artificial mouth playing the note G_2 on the trombone are shown in figures 3.27, 3.28 and 3.29. There are clearly some differences between the form of the lip opening area for the artificial lips when compared to that of the human musicians shown in section 3.3. The opening area of the lips is approximately sinusoidal, but around the point of maximum opening area the behaviour deviates from this simple form. It can be seen that there are 'double' peaks, with the lips closing a little before opening even further. Observing the videos of the lip motion it can be seen that these double peaks are caused by the behaviour of the water inside the lips. As the lips open,

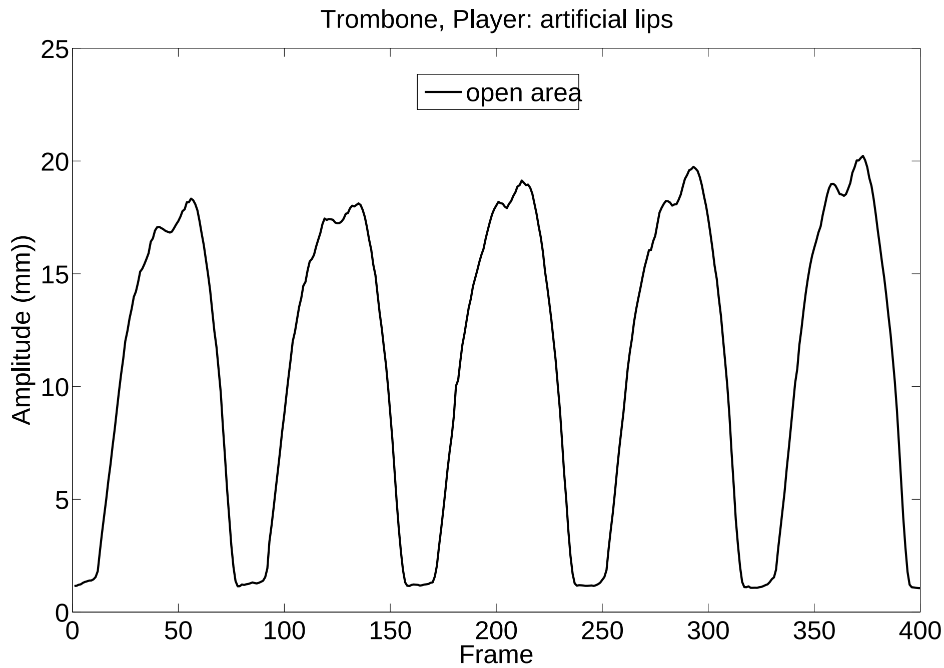


Figure 3.28: *Opening area as a function of time. Note G_2, trombone. Player **artificial lips***

the water inside starts to move, and around the point of maximum lip opening the momentum of the water itself becomes important. As the lip reaches the point of maximum opening area the water redistributes itself, causing the lip itself to move. In order to create a more realistic artificial lip the damping of the substance inside the lip has to be increased. Introducing a colloid, or perhaps some sponge, into the water would increase the viscosity and dampen some of the effects of the water moving around inside the lip. Alternately, a fluid other than water could be used, so long as the viscosity of the new fluid is higher than that of water.

Secondly, it can be seen that the lips of the artificial mouth do not close completely during the cycle. The minimum value of the opening area is

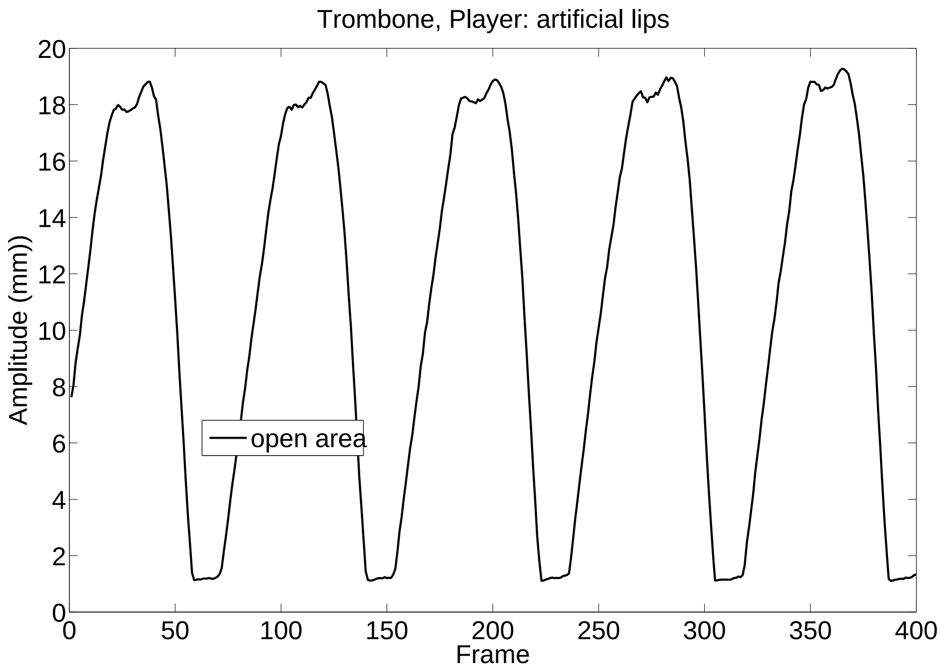


Figure 3.29: *Opening area as a function of time. Note G_2, trombone. Player* ***artificial lips***

approximately 1mm^2, and the lips remain at this value for a significant proportion of the cycle. Examining the video footage confirms this analysis. Figure 3.30 shows a still from the footage corresponding to this point in the cycle. The left hand edge of the lips, circled in red, does not appear to close at any part in the cycle. In fact, this region of the lips does not appear to move at all during the oscillation. Instead, the 'edge' of the motion corresponds

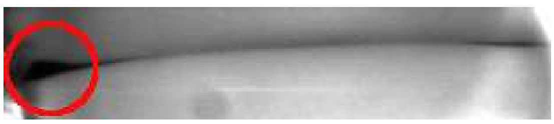


Figure 3.30: *With this embouchure, the lips did not close completely at the sides of the mouth*

to a point further along the lip. It appears that the embouchure that was achieved in this specific case was not an ideal one. However, the artificial mouth was still able to produce a satisfactory tone on the trombone and the results obtained are consistent with those obtained with human musicians.

3.5.3 Artificial lips: area-height relationship

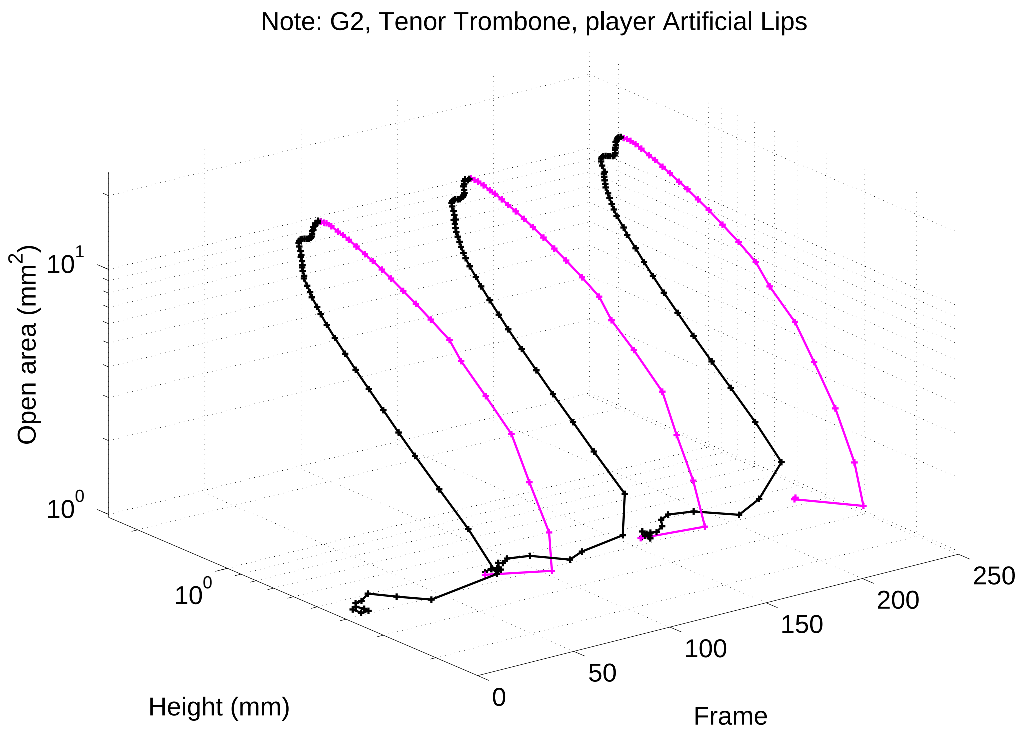


Figure 3.31: *Lip opening area as a function of lip opening height and frame number (time) for three cycles of the note G_2 on the trombone. The opening area and opening height are plotted on a logarithmic scale. The opening phase of each cycle is shown in black, and the closing phase in magenta. Player* ***artificial lips***

Figures 3.31, 3.33, and 3.35 show three typical sets of lip opening area as a function of lip opening height and time (frame number) as recorded using the artificial mouth. Figures 3.32, 3.34, and 3.36 show the 2-D projection of these

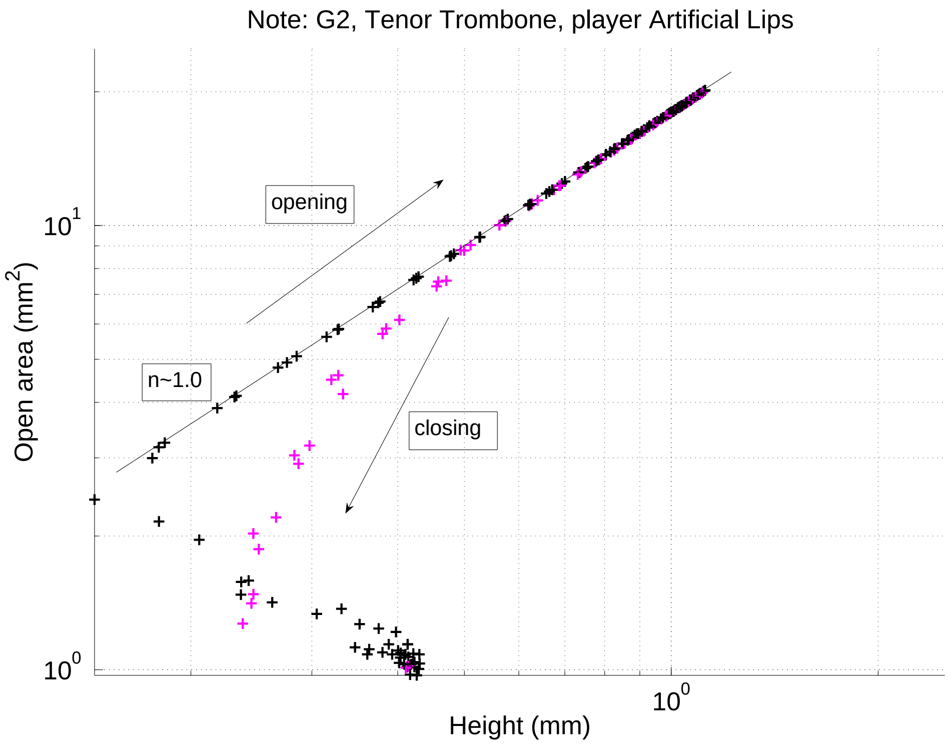


Figure 3.32: *Lip opening area as a function of lip opening height, plotted on a logarithmic scale, for the note G_2 on the trombone. These data correspond to the projection of figure 3.31 onto the $y - z$ axis. The opening phase of the motion is shown in black and the closing phase in magenta. Player **artificial lips***

data onto the area-height plane. All of the lip opening area and height data are plotted on a logarithmic scale in order to extract the value of the exponent n. It is clear that there are several differences to the lip opening behaviour of the artificial mouth when compared to that of the human musicians in section 3.4.

In all three cases, the artificial lips open along a region of constant $n \approx 1.0$, and they remain in this region for the vast majority of the opening phase. When they begin to close, they remain in this region for approximately half of the closing phase at which point the relationship between area and height can no longer be described using a linear fit. It is important to note that the behaviour of the lips at the point of closure has been obfuscated by the fact

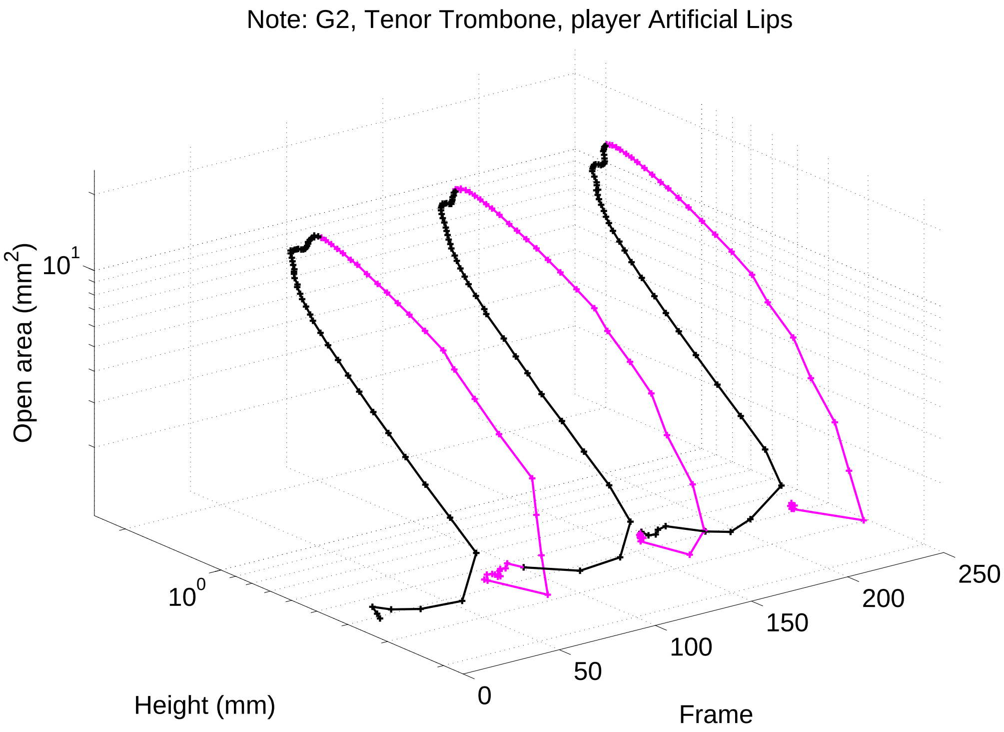


Figure 3.33: *Lip opening area as a function of lip opening height and frame number (time) for three cycles of the note G_2 on the trombone. The opening area and opening height are plotted on a logarithmic scale. The opening phase of each cycle is shown in black, and the closing phase in magenta. Player* ***artificial lips***

that this embouchure did not close entirely (see figure 3.30). For this reason, it is not possible to make precise quantitative analysis of the motion of the artificial lips near the point of closure.

The lips were found to open and close asymmetrically in the case of the three human musicians—the relationship between opening area and opening height was different in the opening phase when compared to the closing phase. In contrast, however, the artificial lips appear to open and close in a remarkably symmetrical manner, with the opening and closing phases being impossible to separate for the vast majority of the cycle. Additionally, in all three cases the value of n in the best defined region is approximately equal to 1. In all

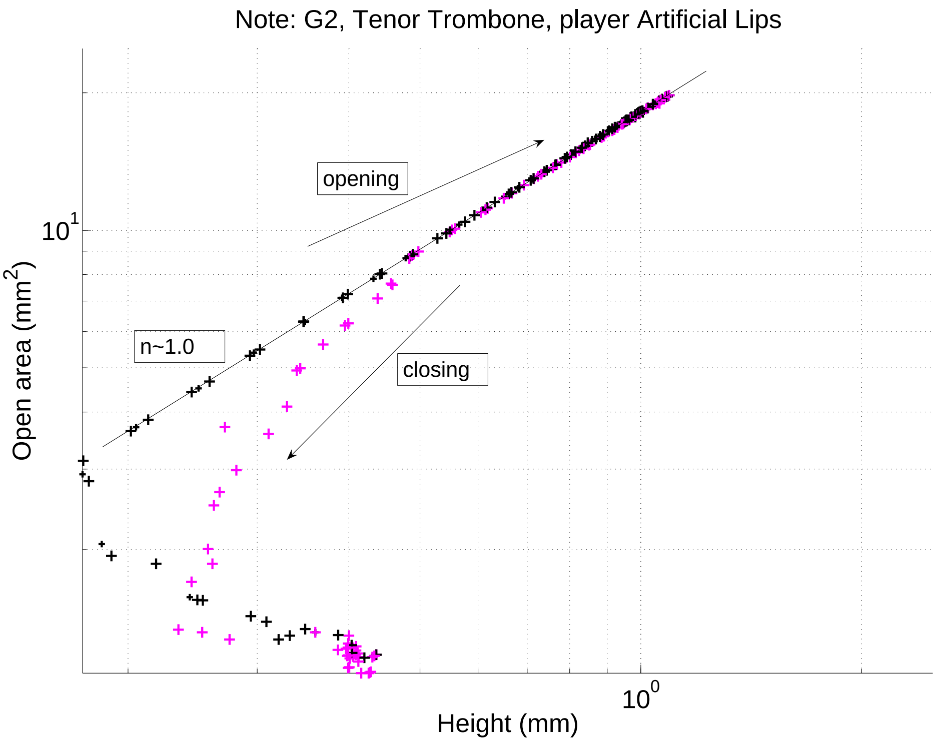


Figure 3.34: *Lip opening area as a function of lip opening height, plotted on a logarithmic scale, for the note* G_2 *on the trombone. These data correspond to the projection of figure 3.33 onto the* $y - z$ *axis. The opening phase of the motion is shown in black and the closing phase in magenta. Player* ***artificial lips***

but one of the recordings made with human players the exponent was > 1. This implies that the way the artificial lips open and close is different to that of human musicians. Indeed, when observing the video footage for the artificial lips, it is clear that the lips tend to open to their full width almost immediately at the start of the cycle with the corresponding open area then depending almost purely on the opening height. In our basic model, when $n = 1$ the opening area is modelled purely as a rectangle of varying height. Thus, $n \approx 1.0$ is not an unexpected or unrealistic value for our artificial lips. However, despite the differences to the behaviour of human lips, it is reassuring that the value of n is consistent for each of the recordings made on the artificial

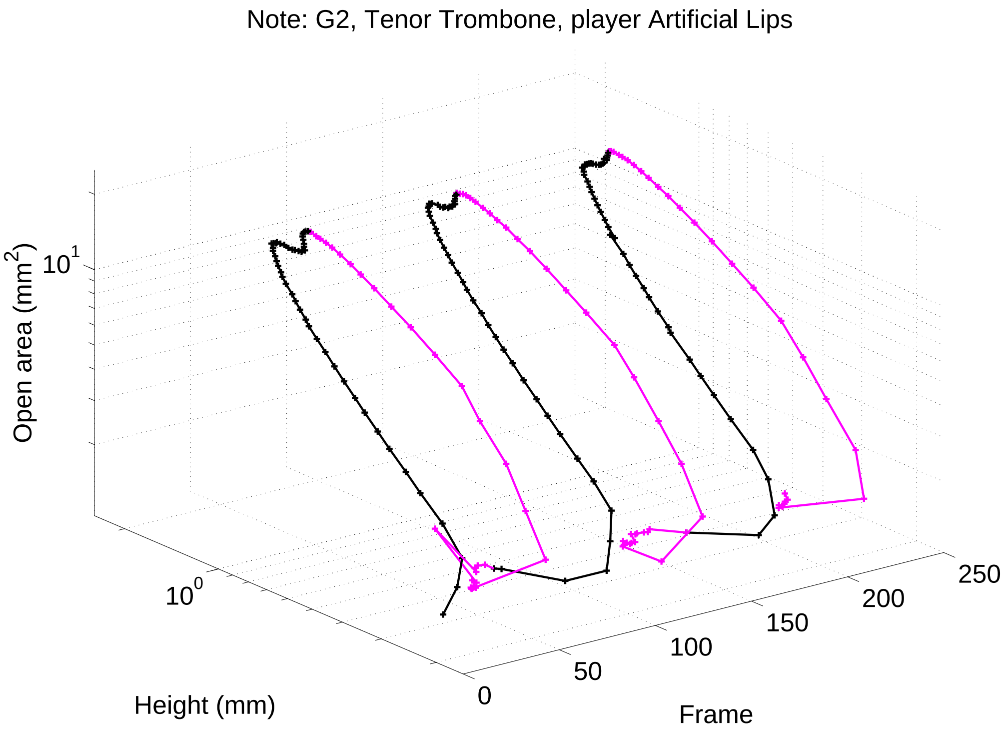


Figure 3.35: *Lip opening area as a function of lip opening height and frame number (time) for three cycles of the note G_2 on the trombone. The opening area and opening height are plotted on a logarithmic scale. The opening phase of each cycle is shown in black, and the closing phase in magenta. Player* ***artificial lips***

mouth—consistency of embouchure was one of the guiding aims of its design. In this respect, the artificial mouth has been very successful.

3.5.4 Lip opening height and lip opening width as a function of time: artificial mouth

Figures 3.37, 3.38, and 3.39 show the variation of lip opening height and width as a function of time for the three recordings made on the artificial mouth. It can be seen that in each case, the lip opening width reaches its maximum value almost instantly, and then remains approximately constant for the majority of

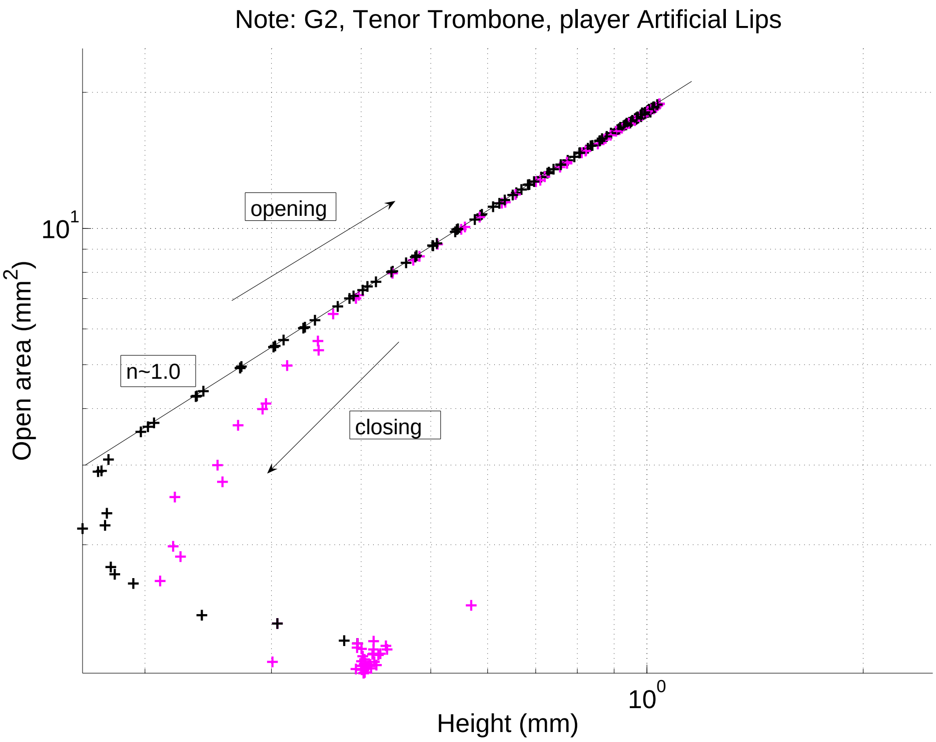


Figure 3.36: *Lip opening area as a function of lip opening height, plotted on a logarithmic scale, for the note* G_2 *on the trombone. These data correspond to the projection of figure 3.35 onto the* $y - z$ *axis. The opening phase of the motion is shown in black and the closing phase in magenta. Player* ***artificial lips***

the cycle. This implies that with this embouchure, in contrast to the behaviour of the human players, the motion does not 'begin' in the centre of the lip but rather that all points along its surface begin to move at the same time. This in agreement with the results of the previous section, where the artificial lips were shown to behave approximately in the same manner as a rectangle of varying height. There do not appear to be any significant hysteresis effects and the lip motion is symmetrical across both opening and closing phases of the oscillation.

In terms of the lip opening height, the behaviour of the artificial lips is more consistent with the behaviour of the human players than in the case of the lip

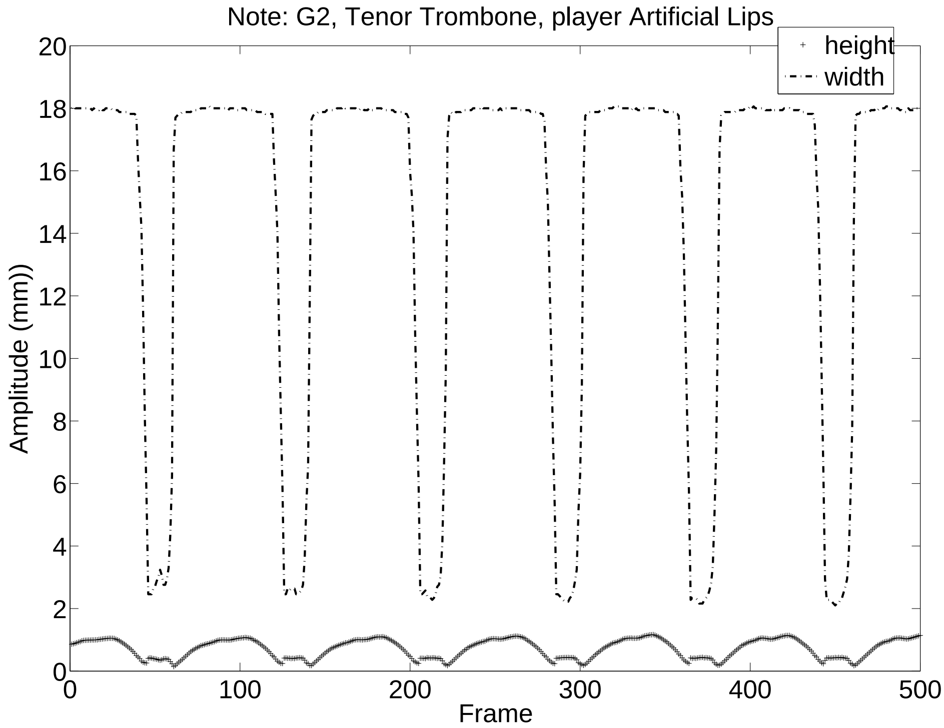


Figure 3.37: *Lip opening height and lip opening width as a function of time. Note G_2, trombone. Player* ***artificial lips***

opening width. The variation in opening height is approximately symmetrical during both stages of the oscillation, and it grows and decreases at a slower rate than the lip opening width. Here, however, there appear to be some small 'double peaks' in the lip opening height. The artificial lips are filled with water and as such are less heavily damped than the lips of a human. The lower damping factor accounts for these double peaks in the maximum values of the opening height.

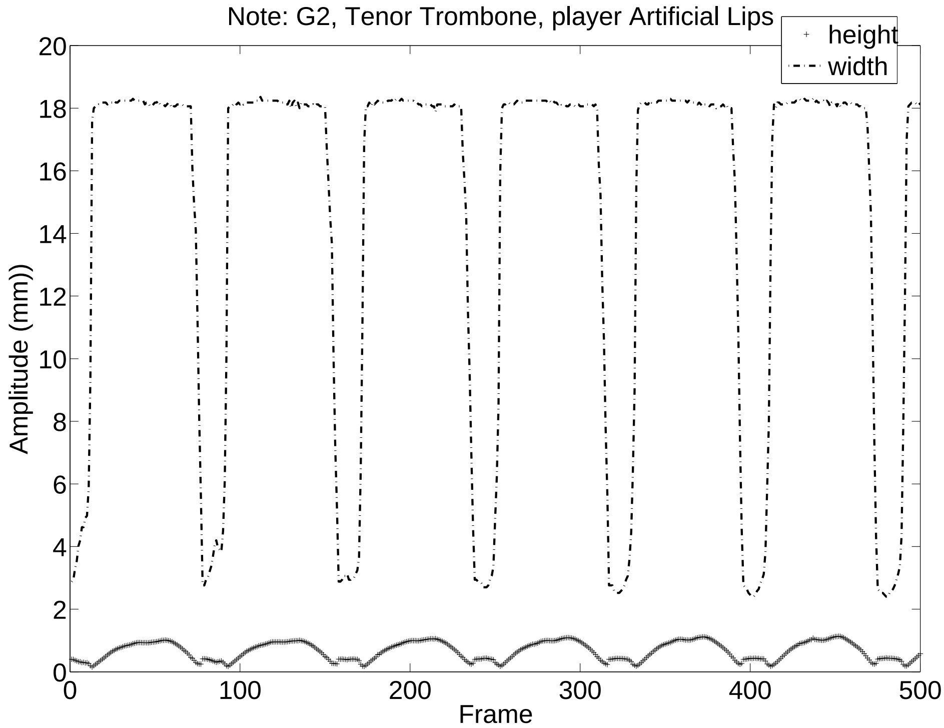


Figure 3.38: *Lip opening height and lip opening width as a function of time. Note G_2, trombone. Player* ***artificial lips***

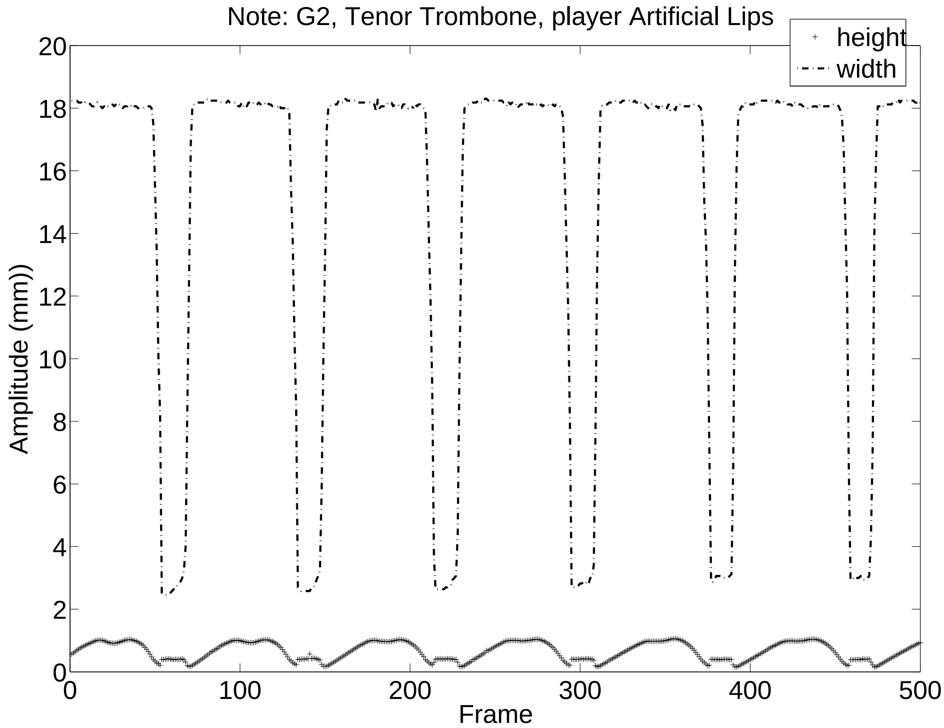


Figure 3.39: *Lip opening height and lip opening width as a function of time. Note G_2, trombone. Player **artificial lips***

3.6 Conclusions

Equipment and experimental methods for quantitative behaviour of the motion of the lips during playing of brass wind instruments were discussed. It was found that for human musicians the relationship between lip opening area and lip opening height could be described using a combination of linear fits, with each fit being used during a different part of the cycle. Around the point of maximum opening the lips tended to open along one region of constant gradient, n, and close along another. There was evidence of hysteresis effects as the lips changed from one region to another. It is possible to hear the differences between computational simulations performed using $n = 1$ and $n = 1.5$ [Gilbert *et al.*, 2006]. It would be an interesting exercise to vary n over the course of a single cycle to see whether or not the simulation was audibly improved. Repeat measurements, on more musicians, are required before firmer conclusions can be drawn. The lip opening width during the steady-state oscillation was shown to be asymmetrical whilst the lip opening height was approximately symmetrical across the opening and closing stages of the motion.

Experiments using an artificial mouth showed that using a mechanical playing device to sound a brass instrument produces results that are both consistent and repeatable. For the artificial lips the relationship between opening area and lip opening height was simpler than in the case of the human musicians. The opening area of the artificial lips tends to behave in the manner of a rectangle of varying height, with the lips reaching their maximum opening width almost immediately. For the majority of the cycle the opening and closing phases of the lip were indistinguishable in terms of the relationship between opening height and width. The motion of the artificial lip during the steady-state was found to be symmetrical in terms of both lip opening width and lip opening height.

It should be noted, however, that we are comparing the behaviour of the lips of human horn players with the lips of an artificial mouth playing the trombone. This is for two reasons—firstly, the current artificial mouth is optimised for trombone playing and it was difficult to use it to form an embouchure suitable for playing the horn. Secondly, previous studies have concentrated on the lips of human trombone players, for example [Copley and Strong, 1996; Richards, 2003; Bromage, 2007] and so an attempt has been made here to widen the scope of experimental investigation by concentrating on horn players. However, the behaviour of the lips of human trombonists and horn players seems to be sufficiently similar that it is not unreasonable to compare the behaviour of the artificial mouth during trombone playing with that of human musicians playing the horn.

Since the artificial lips and the lips of human musicians appear to behave differently around the point of maximum opening, it is desirable to alter the artificial lips to produce more realistic behaviour. It would seem unlikely that the human player is able to control the embouchure precisely enough to directly alter the relationship between lip opening height and lip opening area over a small proportion of the cycle, or to repeat this alteration several hundred times in the course of a single second. Instead, it is more probable that the change in the way the lips open and close is linked to the mechanical properties of the lips themselves—that is, the properties of the tissue and muscle that surround the lips. The current artificial lips are filled with water, and whilst they are capable of producing satisfactory sounds, they are not damped heavily enough (see section 3.5.2) in comparison to the lips of human musicians. Replacing the water with some kind of foam or gel, or perhaps using a sponge or colloid inside the artificial lips may be a good way to produce a more realistic ‘feel’ for the artificial lips without sacrificing sound quality.

The ‘binary’ analysis procedure discussed in section 3.2.1 works successfully for the majority of videos obtained during this work. However, if the lighting of the lips is less than perfect then it is possible that shadows on the lips (particularly in the corners of the mouthpiece) can add ‘noise’ to the area data obtained. In addition, for small opening areas it is hard to select an appropriate threshold by eye. Finally, for some of the footage obtained it was found that the teeth of the player could be seen. The teeth typically lie ‘in’ the open area of the lips and so make it hard to calculate an accurate open area. In order to simplify the analysis process for future work it may be desirable to switch to an alternate method of calculating the open area of the lips. Some kind of edge detection software would appear to be the most appropriate avenue for exploration.

Chapter 4

The behaviour of the lip reed during extremely loud playing

'Ignorant people think it's the noise which fighting cats make that is so aggravating, but it ain't so; it's the sickening grammar they use'

—MARK TWAIN

4.1 The brassy sound

One of the most distinctive features of brass wind instruments is that their timbre is strongly dependent upon the dynamic level at which they are played. At loud levels, the sound becomes recognisably 'brassy' (sometimes described as 'cuivré'). This rather unique tone is produced by an increase in the energy level of the higher harmonics [Backus and Hundley, 1971; Hirschberg *et al.*, 1996; Stevenson and Campbell, 2008] and is commonly used by both composers and musicians as a form of musical expression. Typical waveforms and frequency spectra for brassy and 'non-brassy' playing on the horn are given in figure 4.1 and figure 4.2, clearly demonstrating an increase in the energy of the higher harmonics. It is interesting to note that the effect is more dominant in some instruments than others; for instance, the trombone is generally considered to be brassier than the euphonium. Indeed, some researchers have attempted to assign a 'brassiness coefficient' as a method of musical taxonomy [Gilbert *et al.*, 2007], with promising results.

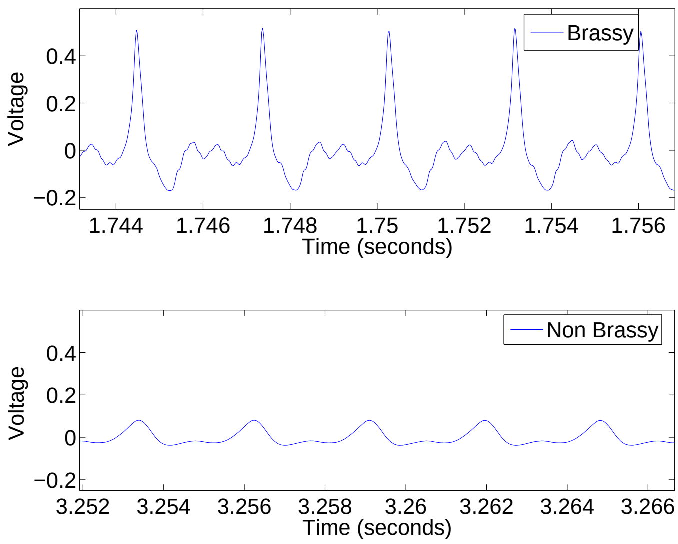


Figure 4.1: *Typical waveforms as heard by the listener for brassy and non-brassy playing on the horn. Note F_4. There is a clear change in the form of the pressure signal*

There have been several suggestions as to the physical mechanism by which the brassy sound is produced. These hypotheses are discussed in the following sections.

4.2 Brassy playing: theory

Backus and Hundley [1971] were among the first to make a serious attempt at identifying the physical mechanism by which harmonics were generated on brass instruments and this paper is still widely cited today. They concluded

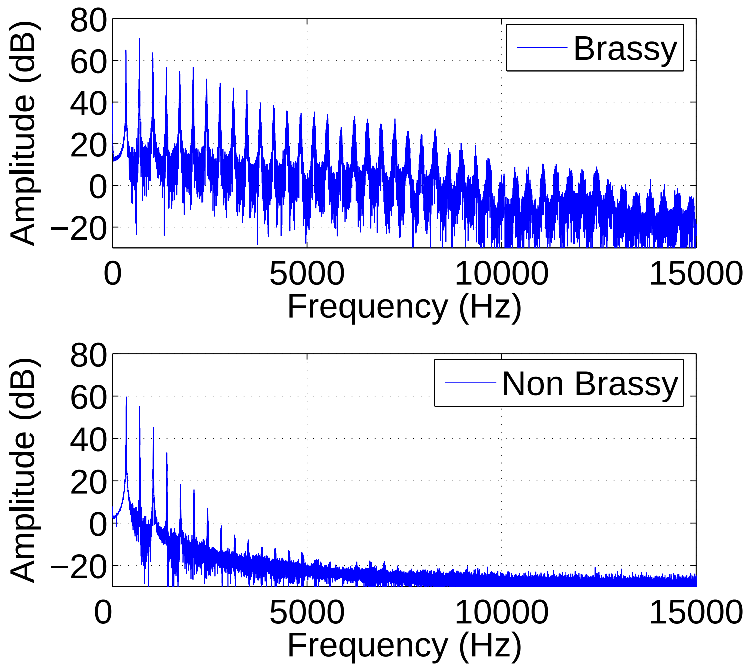


Figure 4.2: *Frequency spectra for the waveforms given in figure 4.1. Note F_4, horn. The increase of the energy in the higher harmonics can be clearly seen*

that nonlinear behaviour of the air column was not a major factor in the production of harmonics, accounting for only a few percent of the total harmonic distortion.

However, Beauchamp [1980] suggested that when brass instruments are played loudly nonlinear propagation within the air column of the instrument could become important and this was confirmed by the work of Elliot and Bowsher [1982]. Hirschberg *et al.* [1996] were able to verify that nonlinear effects were responsible for the formation of shockwaves within the bore of brass instruments. These nonlinear effects have been further verified both experimentally [Pandya *et al.*, 2003] and theoretically [Thompson and Strong, 2001; Msallam *et al.*, 2000]. A brief overview of the theory of nonlinear propagation is given in the following section.

4.2.1 Weak nonlinear propagation

The linear acoustic wave equation is normally written in the following way:

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \tag{4.1}$$

where p is the acoustic pressure, x and t denote position and time, and c is the speed of sound which, in this case, is constant. In order to derive this equation it is necessary to make the assumption that the acoustic amplitudes are small when compared to the mean values of all the quantities concerned. This equation, therefore, is no longer valid when the pressure amplitude of the acoustic wave is no longer insignificant when compared to the mean atmospheric pressure. Inside a brass instrument, such as a trombone, the acoustic pressure amplitude can be as high as 10% of the mean atmospheric pressure [Gilbert, 2006] and as such the linear approximation can no longer be used.

One method of deciding the applicability of the linear approximation is by considering the dimensionless acoustic Mach number, $M = v/c_0$, where v is the acoustic velocity and c_0 is the speed of sound from the linear approximation. When $M \simeq 1$ we are in the 'strongly' nonlinear regime and any attempt at linearising the fundamental equations is impossible. However, for $M \ll 1$, the so-called 'weakly nonlinear' regime, it is still possible to observe significant nonlinear effects. In this regime we are still able to make some use of linear approximations (with appropriate modifications). This is possible because the nonlinear effects are negligible over distances small when compared to one wavelength. However, the nonlinear effects are cumulative and so on the large scale we are able to measure the effects of nonlinear propagation.

For a plane wave, travelling in the forward direction, the nonlinear propagation equation is [Rossing, 2007]:

$$\frac{\partial p}{\partial t} + (c + \nu)\frac{\partial p}{\partial x} = 0 \tag{4.2}$$

It can be shown that when the pressure amplitude exceeds the linear limit the speed of sound can no longer be considered constant. For the weak nonlinear case, the speed of propagation of a wave is given by [Hamilton and Blackstock, 1998]

$$c = c_0 + \nu\left(\frac{\gamma(T) - 1}{2}\right) \tag{4.3}$$

with γ is the ratio of specific heats for the medium in question. The temperature dependence of γ has been made explicit. Combining equations 4.2 and 4.3 we get:

$$\frac{\partial p}{\partial t} + \left(c_0 + \nu\left(\frac{\gamma(T) + 1}{2}\right)\right)\frac{\partial p}{\partial x} = 0 \tag{4.4}$$

This is the weakly nonlinear plane wave equation.

There are, accordingly, two reasons for the distortion of a propagating wave in the weak nonlinear regime. Firstly, the large amplitude acoustic oscillations create alternating regions of compression and expansion within the propagation medium, which in turn affect the local temperature of that medium. Since the speed of sound is temperature dependent in the nonlinear case, these local variations in temperature mean that different parts of the acoustic pressure wave travel at different velocities.

The second effect to consider is that of fluid entrainment. As an acoustic wave travels through a medium, the medium oscillates. If the amplitude of the oscillations is significant (as in the nonlinear case) then when calculating the resulting wave speed of the acoustic pressure wave then we must take into account the oscillation of the medium itself. In effect, an observer would not see a wave travelling at constant velocity c, but instead a wave where the propagation speed was given by $(c + v)$. As a result the top of the wave travels faster than the bottom.

So, the combined effect of the temperature dependence of the wave speed and the fluid entrainment effect is to cause the crest of a pressure pulse within the instrument to travel slightly faster than the 'trough' of the pulse, 'steepening' the wave. If the nonlinear effect is strong enough, and the air column sufficiently long, then this wave steepening can cause shockwaves to be formed within the body of the instrument [Pandya *et al.*, 2003]. It is interesting to note that the nonlinear effect is more significant in instruments with predominantly cylindrical bore profiles (such as the trombone) than predominantly conical instruments (such as the flugelhorn) because conical tubing tends to counteract the nonlinear propagation effect [Hirschberg *et al.*, 1996; Gilbert *et al.*, 2007] .

It is now widely accepted that it is this nonlinear wave steepening and shockwave formation which is primarily responsible for the brassy sound. However, there are still some other suggestions as to alternative mechanisms by which this distinctive timbre may be created, or reinforced.

4.2.2 Wall vibrations

The walls of a brass instrument vibrate as a sound is produced [Knauss and Yeager, 1941], and as the musician plays louder the amplitude of these vibrations increases. There is still much debate as to whether or not the vibrations of the instrument walls adds significantly to the sound produced by the instrument [Kausel and Mayer, 2008; Whitehouse and Sharp, 2008; Nief *et al.*, 2008; Moore *et al.*, 2007]. Moore *et al.* [2005] comment that the effect of bell vibrations seems to vary from instrument to instrument, with studies on trombones tending to support the hypothesis that vibrations of the bell have little effect on the radiated sound [Smith, 1986] whilst studies on trumpets and horns tend to suggest the opposite [Lawson and Lawson, 1985]. With this in mind—and since the brassy sound is very much a distinctive feature of the trombone—it seems unlikely that vibrations in the bell of the instrument alone can cause the dramatic change in timbre to be found in brass instruments when played at their loudest levels. Wall vibrations may contribute to the brassy sound, but they are almost certainly not a primary cause.

4.2.3 Constraints of the lip motion

It has also been suggested by some researchers that the degree to which the lips can open becomes 'saturated' or 'clipped' during extremely loud playing as the movement of the lips becomes constrained by the rim and cup walls of the mouthpiece [Fletcher and Tarnopolsky, 1999; Widholm, 2005; Moore *et al.*, 2005]. This effect, if present, would contribute significantly to the production of a brassy sound. Martin [1942] performed some measurements in which he showed that during mezzo forte playing on the cornet the variation of lip opening area with time was almost sinusoidal. Other studies, using trombones, showed that the open area between the lips did not vary sinusoidally. In fact, the 'closing' part of the lip motion took longer than the 'opening' phase [Copley and Strong, 1996; Bromage *et al.*, 2006]. This effect was more pronounced in large amplitude playing.

Testing the hypothesis of lip constraint during extremely loud playing is one of the major aims of this work.

4.3 Chapter aim

In order to test the hypothesis that the brassy sound is caused by saturation of the lip opening area at large playing amplitude, the high speed digital camera and transparent mouthpieces (detailed in section 3.1) were again put to use. Three musicians—skilled amateurs with many years playing experience—were asked to play pairs of notes at two different playing dynamics; one clearly brassy to the ear and one clearly non-brassy. The lip opening area for each note was captured using the Phantom v4.1 high speed digital camera. Recordings of the pressure fields inside the mouthpiece and radiated from the bell of the instrument were compared for different dynamic level.

4.4 Experimental Method

Experiments for this part of the work were carried out on both tenor trombone and horn. The experimental setup for the trombone can be seen in figure 4.3 and that of the horn in figure 4.4.

4.4.1 Video footage

The players were asked to play two notes; one at a *mezzo forte* (*mf*) level and the other at a clearly brassy dynamic (*ffff*). The Phantom v4.1 high speed camera and transparent mouthpieces (see section 3.2.1) were once again used to film

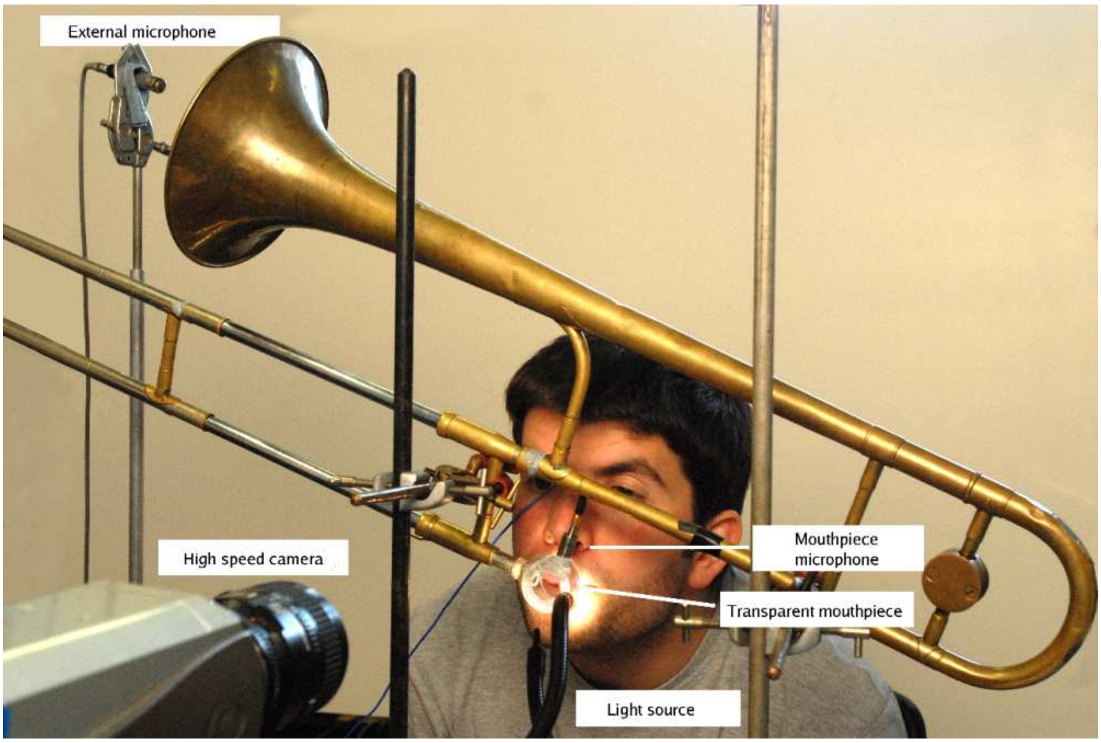


Figure 4.3: *The experimental setup for the trombone during brassy playing. The Phantom camera was used to film the motion of the lips. A PCB 106B pressure transducer was inserted into the transparent mouthpiece (see figure 4.7) and a Brüel and Kjær 4192 microphone used to record the radiated sound*

the motion of the lips of the musicians during performance. Figures 4.5 and 4.6 show a typical set of images captured by the camera for both non-brassy and brassy playing on the tenor trombone.

4.4.2 Pressure signals: extremely loud playing

Typical acoustic pressure amplitudes inside the mouthpiece of a trombone or horn are of order 10^3 Pa, and at the loudest levels can reach 10^4 Pa. Most audio microphones are not designed to measure signals of this magnitude and, indeed, many would be damaged by insertion into such a pressure field. As such, a low sensitivity microphone was needed to record the pressure

Figure 4.4: *The experimental setup for the horn during brassy playing. The Phantom camera was used to film the motion of the lips. A PCB 106B pressure transducer was inserted into the transparent mouthpiece (see figure 4.8) and a Brüel and Kjær 4192 microphone used to record the radiated sound*

in the mouthpiece. A PCB 106B pressure transducer—a low sensitivity microphone—was placed into a hole drilled into the rim of the trombone mouthpiece as can be seen in figure 4.7. In the case of the horn, the mouthpiece rim is not large enough to admit the transducer, and so a short probe attachment was used. Figure 4.8 shows the horn mouthpiece with probe microphone attached.

A second microphone—a Brüel and Kjær type 4192—was used to record the pressure signal radiated from the bell of the instrument at a distance of one bell radius. At this distance from the bell, the microphone picks up a signal

Figure 4.5: *A complete lip cycle for non-brassy playing. There are* 22 *images, spaced equally over a complete cycle. The sequence runs left to right, top row then bottom. Note* $B\flat_3$*, tenor trombone*

Figure 4.6: *A complete lip cycle for brassy playing. There are* 22 *images, spaced equally over a complete cycle. The sequence runs left to right, top row then bottom. Note* $B\flat_3$*, tenor trombone*

Figure 4.7: *A hole with diameter equal to that of the PCB 106B pressure transducer was drilled into the wall of the mouthpiece (left). The 106B could then be inserted into the mouthpiece so that the diaphragm was flush with the interior wall of the mouthpiece (right). The transducer was sealed to ensure there were no air leaks*

which is equivalent to that obtained by recording the sound at many different points throughout the room and integrating [Benade, 1976]. This means that the resultant signal gives as true a representation of the instrument output as possible.

Both the 4192 and the 106B microphones were connected to Brüel and Kjær PULSE data acquisition hardware. PULSE is a combination of hardware and software designed for measuring and analysing acoustic signals [Brüel and Kjær, 2009]. In this experiment, it was used to record the pressure signals from both microphones. No further signal processing was performed using PULSE. Each pressure signal was exported as an Ascii text file (*.txt) and was then read into MATLAB for analysis.

4.5 Results: pressure signals

The signals obtained using the PCB 106B inserted into the mouthpiece are discussed in section 4.5.1 and the radiated sounds, recorded using the Brüel

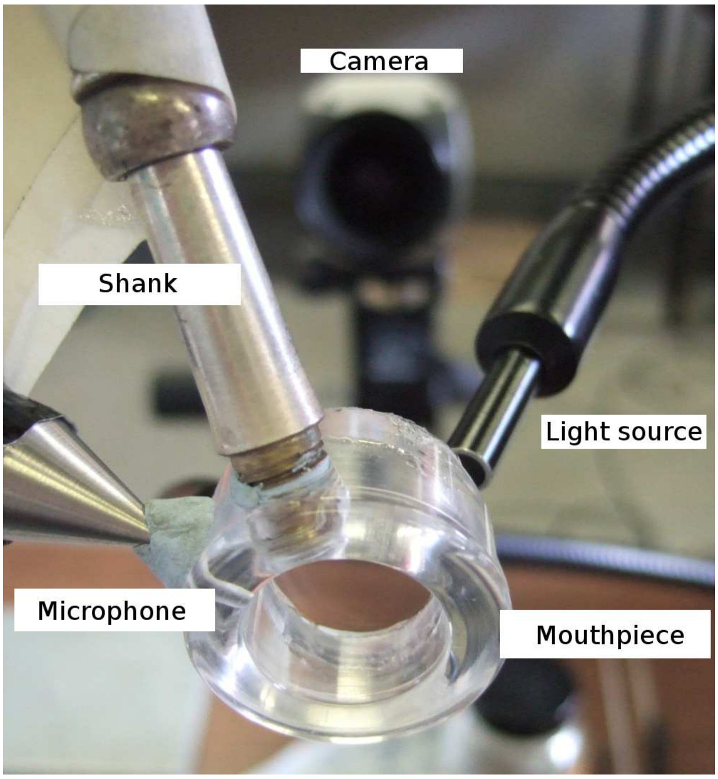


Figure 4.8: *The transparent horn mouthpiece with PCB microphone attached. A small hole was drilled in the wall of the mouthpiece and a short probe attachment inserted. This is the view seen by the player during experiments. The light source and high speed camera can also be seen*

and Kjær 4192, are given in section 4.5.2.

4.5.1 Mouthpiece pressure signals

Figures 4.9 and 4.10 show typical mouthpiece pressure waveforms for brassy and non-brassy playing for notes $B\flat_3$ and F_3 on the tenor trombone as played by player DMC. Each figure shows a repeat measurement, demonstrating that the results obtained are consistent across multiple measurements. Figure 4.11 contains typical mouthpiece pressure waveforms for brassy and non-brassy playing on the horn by player JC. This figure shows information for two notes,

C_4 and F_3. There is a DC offset of approximately 2 kPa in all of the mouthpiece pressure data.

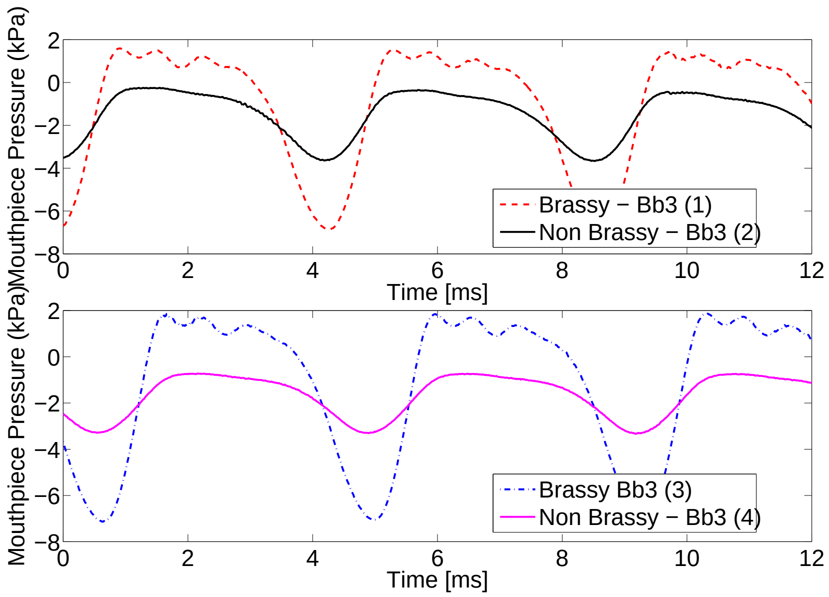


Figure 4.9: *Mouthpiece waveforms for brassy and non-brassy playing. Two recordings of note B♭3, player DMC, tenor trombone. There is a DC offset of approximately 2kPa*

Turning our attention first to the notes recorded on the trombone, we see that all of the non-brassy waveforms are very similar in form. For the majority of the cycle, the pressure is approximately constant but there is pressure drop and then rise which lasts for approximately one third of the cycle. During this time the pressure changes by at most 3kPa. This drop and rise in pressure is clearly controlled by the opening and closing of the lips.

On examining the corresponding brassy mouthpiece pressures we can see that in general terms the form of the pressure signals is broadly similar to that of the non-brassy recordings. For most of the cycle the pressure is

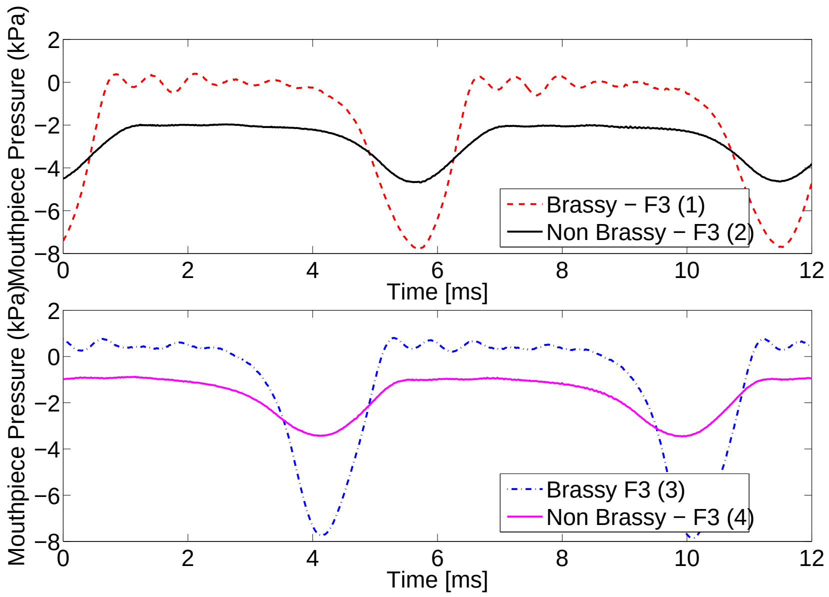


Figure 4.10: *Mouthpiece waveforms for brassy and non-brassy playing. Two recordings of note F3, player DMC, tenor trombone. There is a DC offset of approximately 2kPa*

approximately constant—apart from a few high frequency 'ripples'—and there is a drop and then rise in pressure that again lasts for approximately one third of the cycle. Here, however, the change in pressure is much larger, as expected for large amplitude playing: the pressure drop is between 8 and 10kPa, more than double that of the non-brassy case. It should be noted that the musicians were not playing at the very limit of amplitude—they could have played louder—but were still well inside the brassy regime.

One of the predictions of the theory of nonlinear propagation, outlined in section 4.2.1, is that the distortion is dependent on the maximum rate of change of mouthpiece pressure, $(\frac{\partial P_m}{\partial t})_{max}$. Hirschberg *et al.* [1996] predicted that a shockwave would be formed once the wave had propagated a distance

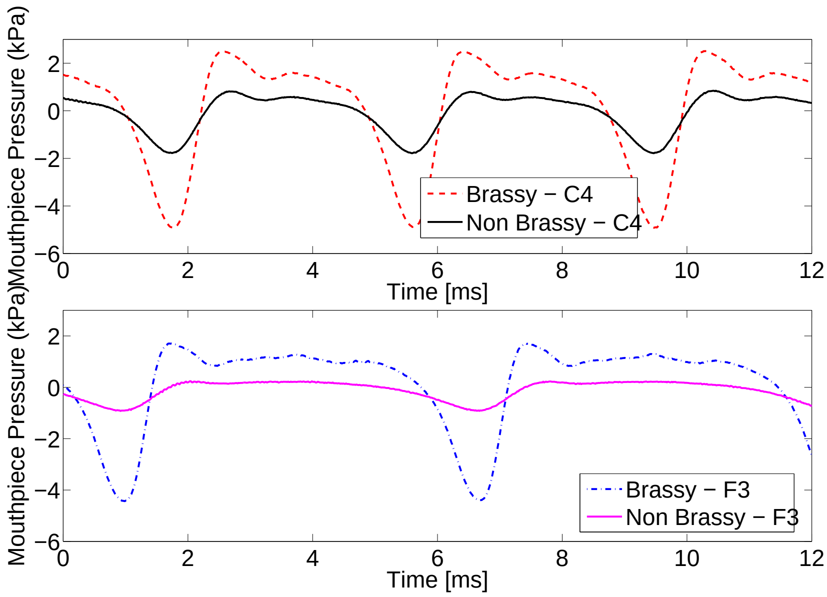


Figure 4.11: *Mouthpiece waveforms for brassy and non-brassy playing. Notes C_4 (upper) and F_3 (lower) on the horn. Player JC. There is a DC offset of approximately 2kPa*

$$x_s \propto \frac{1}{(\frac{\partial P_m}{\partial t})_{max}} \tag{4.5}$$

so that the greater the rate of change of mouthpiece pressure, the shorter the critical distance x_s becomes. Equivalently, for an instrument of fixed length, the greater the rate of change of mouthpiece pressure, the more nonlinear distortion there will be. It is obvious from the mouthpiece pressure signals that the rate of change of mouthpiece pressure is much higher in the case of brassy playing as opposed to non-brassy. The largest rise in pressure takes approximately the same proportion of the cycle for both cases, but in the brassy case the change in pressure is three or perhaps even four times higher. Clearly the mouthpiece pressure signals are consistent with the nonlinear theory.

Examination of figure 4.11 shows that the behaviour of the mouthpiece pressure signals for playing on the horn is very similar to that on the trombone. The non-brassy signals have a maximum pressure drop of around 2 kPa and the brassy signals have a correspondingly higher drop of between 6 kPa and 8 kPa. Once more, the rate of change of pressure in the mouthpiece is much higher in the brassy case than in the non-brassy case. It is clear that for two different musicians, playing multiple notes on two different instruments, that there are many similarities between mouthpiece pressure signals. In all cases, most importantly, the form of the mouthpiece pressure signal does not change dramatically between non-brassy and brassy playing. The amplitude increases, as expected, but in general terms the waveforms are broadly similar.

4.5.2 Radiated pressure signals

Figures 4.12 and 4.13 contain the radiated pressure waveforms corresponding to the mouthpiece waveforms in figures 4.9 and 4.10—i.e the waveforms heard by the listener for the notes F_3 and $B\flat_3$ on the trombone, player DMC. Figure 4.14 shows the radiated sound for the notes F_3 and C_4 on the horn, player JC. Again, these correspond to the mouthpiece pressure signals given in figure 4.11.

Beginning again with the measurements taken on the trombone we can see immediately that there is a dramatic change in the form of the pressure signal from non-brassy to brassy playing. In the non-brassy case, the maximum amplitude of the signal is a few tens of Pa, but in the brassy case there is a large pressure spike whose amplitude is several hundred Pa. Comparing the relative amplitudes of the mouthpiece pressure signals to the radiated sounds, we can see that an increase in mouthpiece pressure by factor 3 has led to an

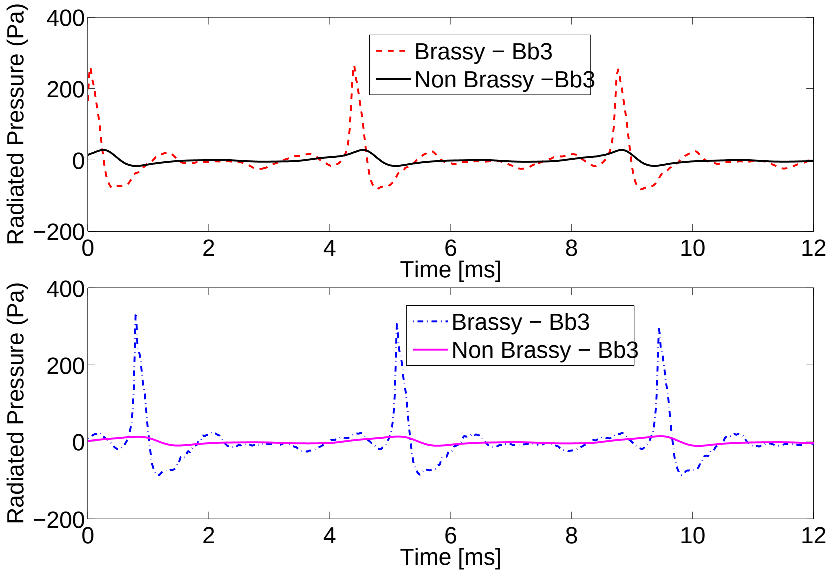


Figure 4.12: *Radiated waveforms for brassy and non-brassy playing. Player DMC. Notes B♭3 on the tenor trombone*

increase in radiated pressure by factor 10.

Nonlinear propagation implies distortion of the pressure wave, which can in turn lead to the formation of a shockwave. The large amplitude spikes that are shown here are clear evidence that there is shockwave formation within the body of the instrument, in agreement with the results of both Hirschberg *et al.* [1996] and Thompson and Strong [2001].

The radiated sound pressures for the horn, shown in figure 4.14, are once again consistent with their trombone counterparts. The differences in amplitude between brassy and non-brassy are an order of magnitude higher than in the mouthpiece pressure signals. However, the horn is not as loud as the trombone—the large amplitude spikes that signal shockwave formation have an amplitude of less than 100 Pa.

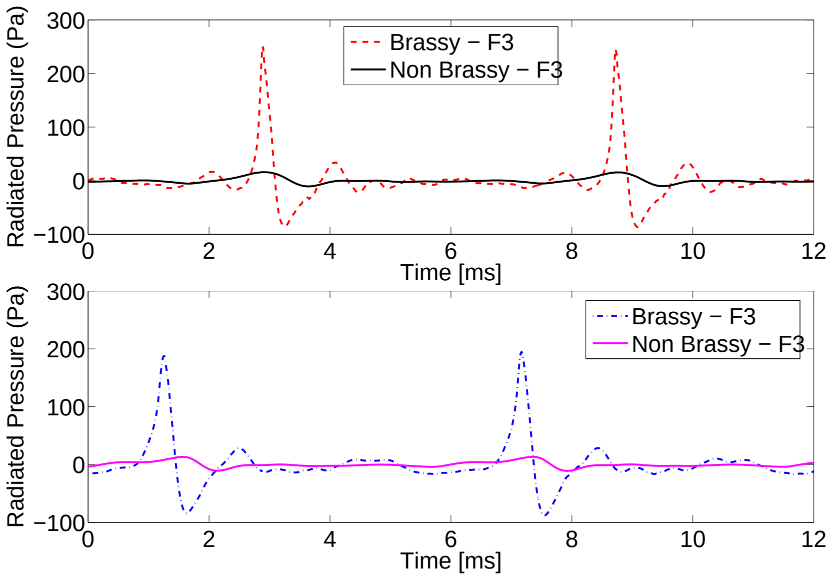


Figure 4.13: *Radiated waveforms for brassy and non-brassy playing. Player DMC. Notes F_3 on the tenor trombone*

We now continue with a more quantitative analysis of both mouthpiece and radiated pressure signals.

4.5.3 Spectral centroids

The spectral centroid represents the distribution of power over frequency and as such allows us to quantitatively measure the increase in energy of the higher harmonics. It is defined as

$$F_{SC} = \frac{\sum_{i=1}^{n} F_i A_i}{\sum_{i=1}^{n} A_i}, \tag{4.6}$$

where F_i is the frequency of the i^{th} harmonic and A_i represents the amplitude

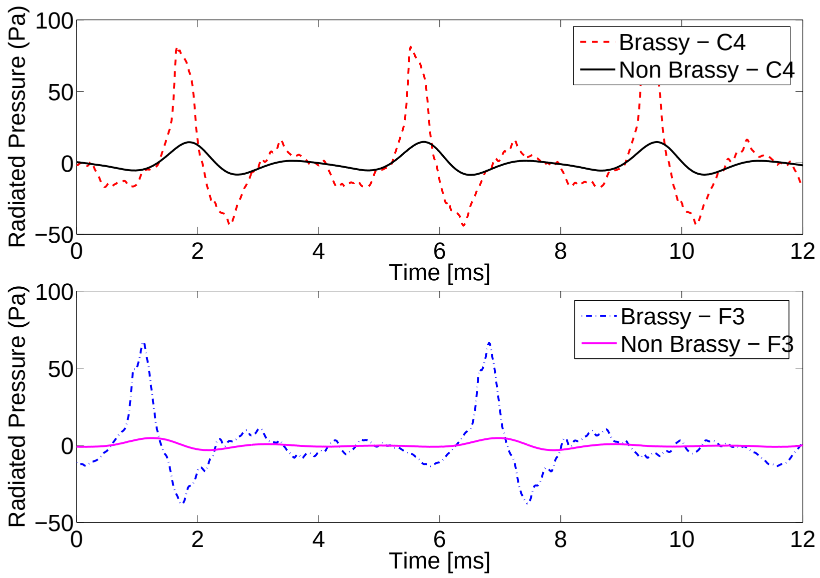


Figure 4.14: *Radiated waveforms for brassy and non-brassy playing. Player JC. Notes C_4 and F_3 on the horn.*

of that harmonic.

In order to calculate the spectral centroids for the notes recorded on the trombone a piece of MATLAB software, written by David Skulina [2009] of the University of Edinburgh, was used. The software takes a wave file (*.wav) as its input. The user can then define the noise level in the recording and the frequency range over which to calculate the centroid. The program uses the native MATLAB FFT routine and then uses a numerical method to calculate the spectral centroid. For all the calculations performed the noise floor and frequency range were kept constant.

The spectral centroids calculated for both the mouthpiece and radiated pressures during both brassy and non-brassy playing on the trombone are shown in table 4.1. For the note F_3 on the trombone, during non-brassy playing

		Mouthpiece pressure			Radiated pressure		
Instrument	**Note**	$SC(nb)$	$SC(b)$	$\frac{SC(b)}{SC(nb)}$	$SC(nb)$	$SC(b)$	$\frac{SC(b)}{SC(nb)}$
Trombone	B♭3	304	369	1.2	716	1816	2.5
	F3	251	392	1.6	562	2462	4.4
Horn	C4	425	504	1.2	559	1258	2.2
	F3	422	623	1.5	655	1150	1.8

Table 4.1: *Spectral centroids (SC) for both non-brassy (nb) and brassy (b) notes, calculated for both the mouthpiece pressure and the radiated sound. The spectral centroid is given in units of Hz. Player DMC*

the spectral centroid increases from 251 Hz in the mouthpiece to 562 Hz in the radiated sound—an increase of factor 2.2. In the case of brassy playing, the centroid increases from 392 Hz to 2462 Hz, an increase by factor 6.3. Since the bell of a brass instrument acts as a high pass filter [Backus, 1976] we would naturally expect the centroid to increase between the mouthpiece and the radiated sound. The question is: to what extent is the increase caused by the high pass filtering of the bell and to what extent by nonlinear propagation? Using a linear model of the bell it was possible to make an estimate of how much of the increase in spectral centroid was due to nonlinear propagation and how much due to the filtering effect of the bell.

4.5.4 Estimating the nonlinearity using a linear filter

Three of the non-brassy recordings on the trombone were used to calculate an approximate 'transfer function' for the trombone. This was done by comparing frequency spectra for the signals recorded in the mouthpiece to the signals captured outside the bell. This provided a 'linear filter' function for the instrument in question. This was done in the following way:

1. Three recordings of mouthpiece pressure and corresponding radiated sound were made for non-brassy playing on the trombone in question.

2. Each recording had a Fourier transform applied and the amplitude of each of the first ten harmonics noted.

3. For each pair of mouthpiece and radiated sound pressures, the corresponding increase (or decrease) in amplitude of each harmonic (due to the high pass filtering of the bell) was calculated. This was then averaged over the three recordings. In this way, a basic linear model of the filtering effect of the instrument was created.

Applying this linear function to the signals measured in the mouthpiece during brassy playing meant that it was possible to make an estimation of what the radiated sound would be should the instrument behave purely in a linear fashion. Comparing the measured (i.e nonlinear) output of the instrument with the estimated (linear) output allows us to make an estimate of the effect of the nonlinearity. In order to perform this comparison, a recording was made of the mouthpiece pressure and radiated sound during brassy playing. These recordings were then subject to the same Fourier transform that was applied to the non-brassy recordings. The 'linear filter' was then applied to the Fourier transform of the brassy mouthpiece signal in order to calculate a 'linear' frequency spectrum for brassy playing. Equation 4.6 was then used to calculate the spectral centroid. For the note F_3 this calculated linear spectral centroid was found to be 870 Hz. However, when the same calculation was performed using the information taken from the Fourier transform of the *recorded* brassy sound the centroid was 2462 Hz. It has to be concluded that the majority of spectral enrichment corresponds to nonlinear propagation.

Returning to table 4.1 we see that for the note F_3 on the trombone, the spectral centroid of the mouthpiece pressure increases by a factor 1.6 in the transition from non-brassy to brassy playing. On the other hand, the ratio between the corresponding radiated centroids is much larger—4.4. The note $B\flat_3$ on the trombone shows a similar trend. This is strongly suggestive that the primary source of the brassy sound comes not from within the mouthpiece of the instrument, but instead comes further downstream before the sound is radiated to the air. This quantitative analysis of the spectral centroid agrees with our qualitative visual analysis of the pressure signals in section 4.5.1 and section 4.5.2.

4.6 Results: lip opening area

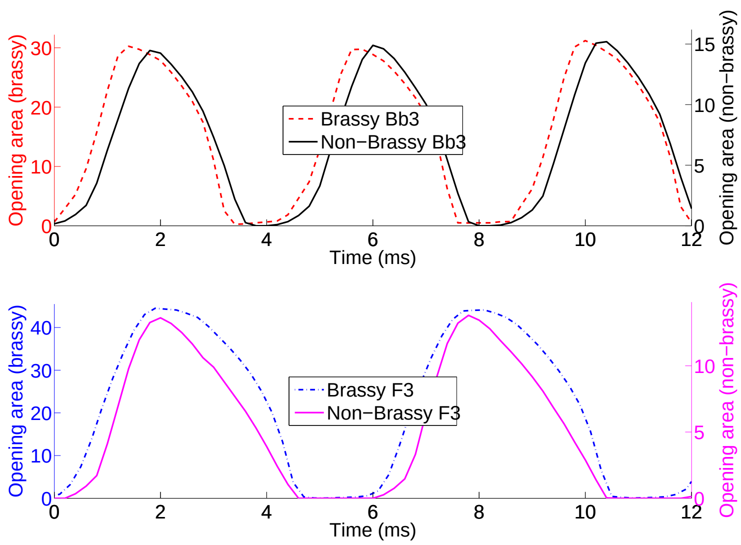


Figure 4.15: *Lip opening areas for brassy and non-brassy playing for the notes $B\flat_3$ and F_3 on the trombone. All areas are given in mm^2. The data pairs share a common time-axis but each data set has its own y-axis, effectively normalising the data for ease of comparison. Player DMC*

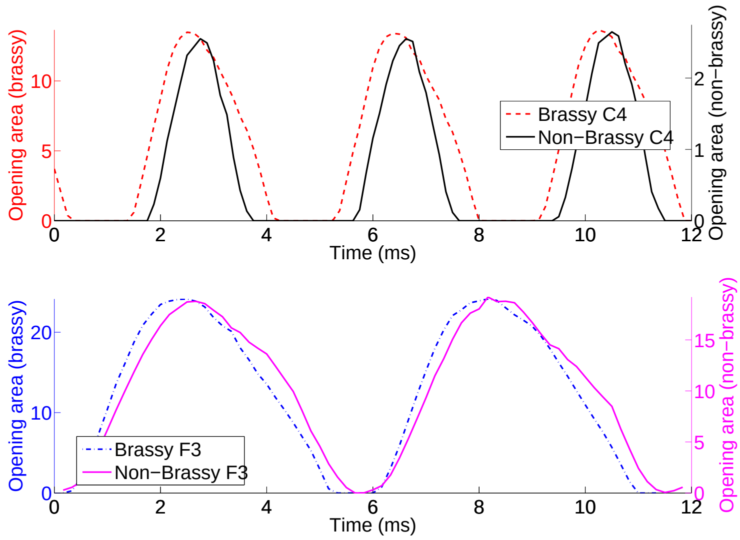


Figure 4.16: *Lip opening areas for brassy and non-brassy playing for the notes F_3 and C_4 on the horn. All areas are given in mm^2. The data pairs share a common time-axis but each data set has its own y-axis, effectively normalising the data for ease of comparison. Player JC*

A previous study, by Bromage [2007] found that the width of the lip opening increased quickly in the early part of the vibration cycle, and then remained at a constant value for much of the rest of the cycle. These findings are supported somewhat by the data shown in section 3.4. However, during this motion, the lip opening height varied continually so that the lip opening area was also continually changing. For louder notes, the width was constant for a greater proportion of the cycle than for quieter playing.

Figure 4.15 shows typical lip opening areas for brassy and non-brassy playing on the tenor trombone. Two notes are shown, $B\flat_3$ and F_3, and the player is DMC. Figure 4.16 shows the lip opening area for the notes F_3 and C_4 played on the horn by player JC. The brassy/non-brassy 'pairs' are displayed on a common time-axis but each data set has its amplitude displayed on a separate y-axis (brassy on the left, non-brassy on the right). This allows us to effectively normalise the data for ease of comparison.

For the notes recorded on the trombone, it is immediately obvious that there are few stark differences between brassy and non-brassy playing. At first glance, the brassy lip opening areas are nearly identical to their non-brassy counterparts. There are certainly none of the major differences that we would expect to see if the lip opening area was somehow being constrained or saturated. However, there are some subtle differences between the extremely loud data and that recorded at a more moderate volume. In the brassy case, the lip open area opens quicker than in the non-brassy. It then appears to close gradually before the gradient of the curve suddenly steepens dramatically. The non-brassy notes, however, appear to close at a constant rate.

Turning now to figure 4.16 we see that the behaviour of the horn is again very similar to that of the trombone. The most obvious difference between the two instruments is that for the horn the amplitude of lip opening area is much smaller. For the note F_3, the open area of the trombone players' lips is approximately twice that of the horn players' during extremely loud playing. Amplitude aside there are few differences between the data recorded on the trombone and on the horn. Again, in the case of brassy playing the lip opening area opens quickly and then closes at a slightly slower rate. The lips of the horn player, however, do appear to close at a more constant rate than that of the trombonist.

Figure 4.17 shows three recordings of the note F_3 played at a non-brassy level on the horn by player LN. Figure 4.18 shows another three recordings of the same note by the same player, but at a brassy playing dynamic. These data sets seem to be slightly less 'sinusoidal' than those of the player JC. However, these data were recorded at a lower resolution (128x128 pixels) and it may be that this has caused some unwanted quantisation effects. Regardless of the shape of the data, however, it is clear that the motion of the lips for player LN is remarkably consistent. In the brassy case, in particular, the lip opening curves are very similar in nature, and in amplitude even more so. Once again we see no saturation or clipping of the lip opening area at any playing dynamic.

In conclusion, the only obvious difference between brassy and non-brassy playing is that, as expected, the brassy lip open areas have a larger amplitude than their non-brassy counterparts. For each brassy/non-brassy pair of measurements, the waveforms of the lip open area as a function of time are very similar, and do not show evidence of clipping, saturation, or constraint in the brassy regime.

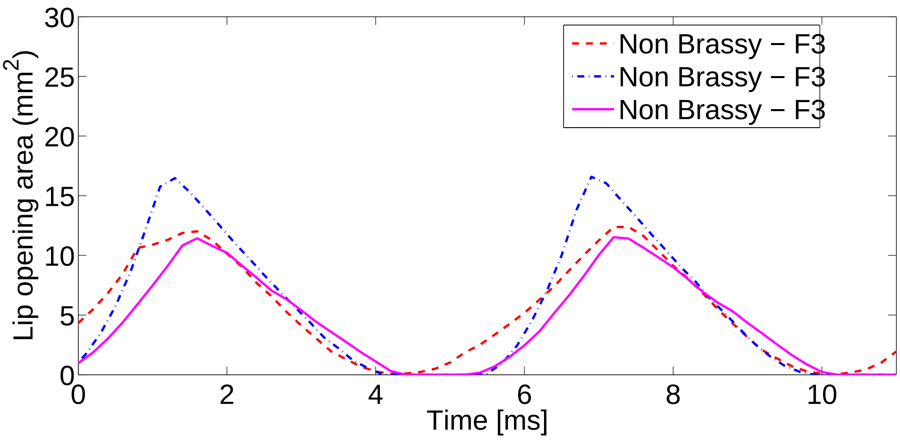


Figure 4.17: *Lip opening areas for three recordings of the note F_3 played at a non-brassy level on the horn. Player LN*

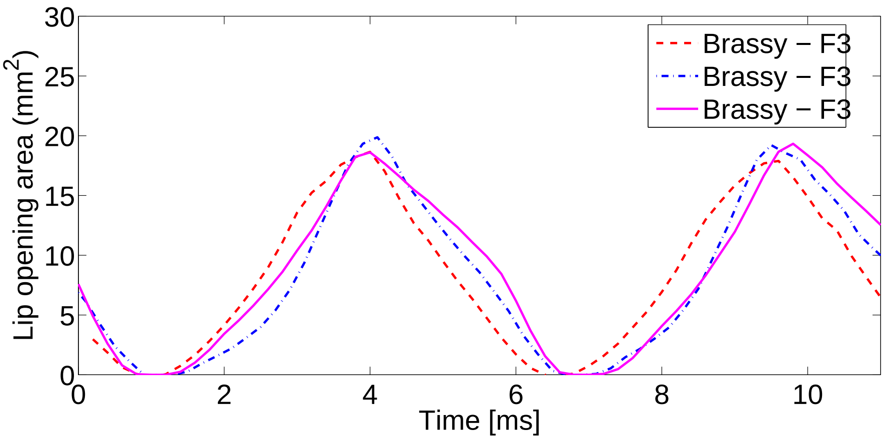


Figure 4.18: *Lip opening areas for three recordings of the note F_3 played at a brassy level on the horn. Player LN*

4.7 Three-dimensional motion of the lips during extremely loud playing

We have already seen in section 4.6 that there does not appear to be any radical change in the behaviour of the lip opening area during playing at loud dynamic. However, it is clear that during playing the lips do not move purely in one plane of motion. For this reason, an attempt was made to discover whether or not the three dimensional motion of the lips could make a contribution to the brassy sound. Copley and Strong [1996] used a stroboscopic method to investigate the longitudinal motion of the lips, but they did not consider the case of extremely loud playing. Newton [2008] used a high speed camera to study the three dimensional motion of a single point on a pair of lips belonging to an artificial mouth. The aim of this part of the thesis is to investigate the three-dimensional motion of the lips of human musicians at extremely loud volumes.

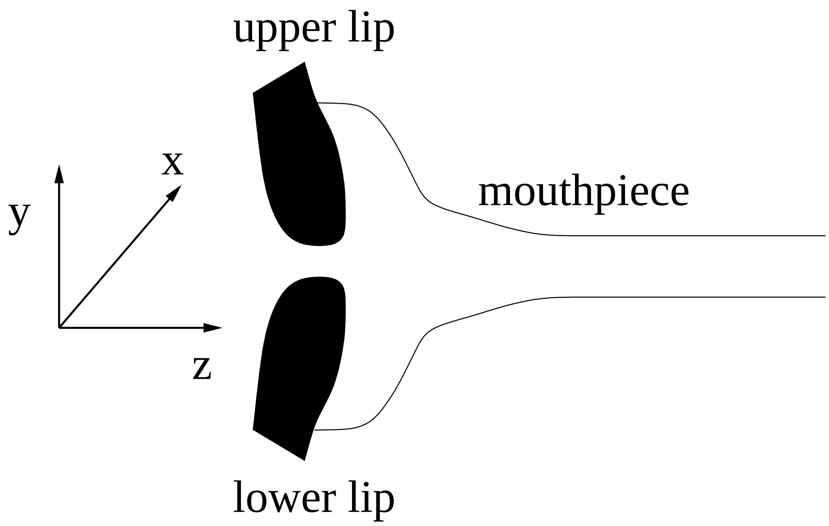


Figure 4.19: *The lips oscillate not only vertically (the y-direction) but also in the x (from one side of the face to the other) and z-directions (in the direction of the airflow)*

4.7.1 Mouthpiece with side window

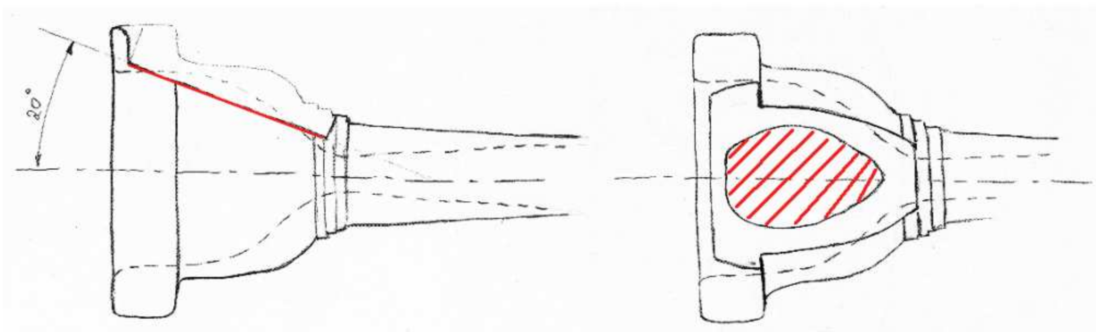


Figure 4.20: *Schematic of the mouthpiece with side window. The external layer of perspex was machined down and replaced with an optical window (shown in red). Based on a drawing by J. Chick [Chick, 2009]*

A new mouthpiece was constructed with a transparent side window in order to capture the motion of the lips in the $y - z$ plane (as defined in figure 4.19). This mouthpiece was a modification of a commercial bass trombone mouthpiece by Kelly [Kelly, 2009]. A schematic of the mouthpiece can be seen

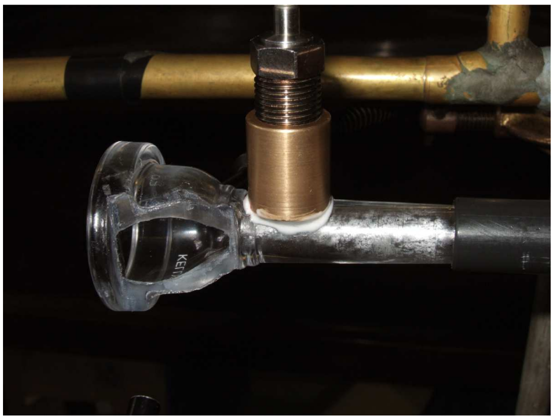


Figure 4.21: *A photograph of the mouthpiece showing the window and PCB microphone adaptor*

in figure 4.20. The external perspex was machined down on one side of the mouthpiece and an optical glass window fitted. This window can be seen in red on the left hand side of figure and on the right hand side of the same figure the window is marked with red stripes. A photograph of the finished mouthpiece is shown in figure 4.21. The window allowed a significant portion of the lips to be seen at an angle almost perpendicular to the players' face, as can be seen in figure 4.22.

The shank of the mouthpiece had an adaptor fixed onto it in order to mount a PCB microphone. This adaptor is designed so that the pressure in the mouthpiece can be measured directly without the need for a probe attachment.

Since horn mouthpieces are considerably smaller than their trombone counterparts it was not practical to make a horn mouthpiece with similar design.

4.7.2 Measurements: filming in the $y - z$ plane

Measurements were made on three different trombonists playing the same tenor trombone. All of the musicians had many years playing experience.

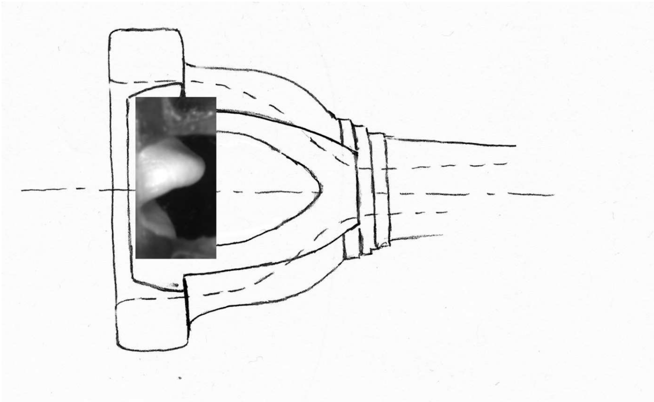


Figure 4.22: *A significant portion of the lips can be seen through the window*

They were asked to play a variety of different pitches in pairs—one at a *mezzo forte* dynamic and the second as loud as possible (i.e *ffff*). A Brüel and Kjær 4192 microphone was used to record the sound radiated from the bell and a PCB 1016B pressure transducer was inserted into the adaptor on the mouthpiece shank in order to capture the pressure inside the mouthpiece.

The Phantom v.4 video camera (see section 3.1) was used to film the lips at a rate of approximately 5000 frames per second. Using the triggering method detailed in section 5.4 the camera footage was synchronised with the pressure signals recorded in the mouthpiece and radiated from the bell of the instrument in order to allow comparison of the motion of the lips with the resulting pressure.

4.8 Results: filming in the $y - z$ plane

Figures 4.25 and 4.26 show one complete cycle of lip motion (the $y - z$ plane, as seen from the side) for the note $B\flat_2$ played at both *mf* and *ffff* by player JG. The corresponding mouthpiece pressure signal is also shown. The red dot on

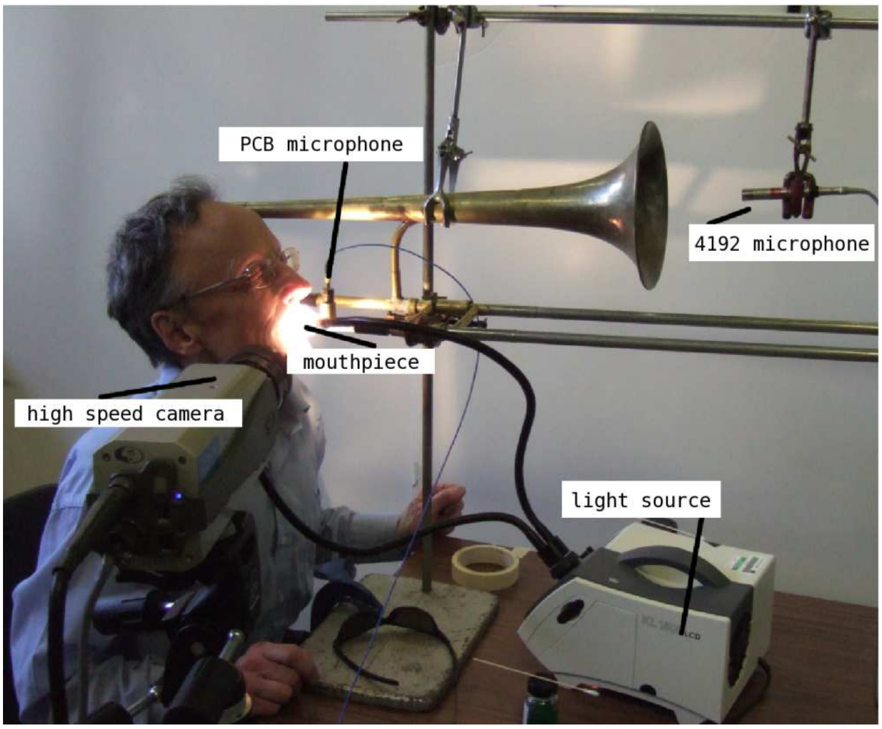


Figure 4.23: *The complete experimental setup, showing the position of the mouthpiece, camera, and microphones. For the experiments in the $y - z$ plane, the instrument was oriented in a more familiar manner*

the pressure signal indicates the point in the cycle corresponding to the image above. Figures 4.27 and 4.28 display the same information but for player MF.

Further examples of complete lip cycles in the $y - z$ plane with corresponding pressure signals are given in Appendix A. Figures A.1, A.2, A.5, and A.6 provide further comparison of the sideways (y-z) lip motion with mouthpiece pressure for the notes F_3 and $B\flat_1$ (the pedal note) as played by player JG, whilst figures A.3 and A.4 show the note F_3 as recorded by player MF. Comparing all of these figures, we see that the motion of the lips is very similar for both players. In addition, the results taken with player DMC (not shown graphically here) are also consistent with that of JG and MF.

Player	Note	Horizontal (mm)	Vertical (mm)
JG	$B\flat_1$ (b)	9	9
	$B\flat_1$ (nb)	7	6
	$B\flat_2$ (b)	9	10
	$B\flat_2$ (nb)	5	6
	F_3 (b)	7	8
	F_3 (nb)	5	6
	F_4 (b)	5	5
	F_4 (nb)	2	2
MF	$B\flat_1$ (b)	9	8
	$B\flat_1$ (nb)	7	6
	$B\flat_2$ (b)	7	7
	$B\flat_2$ (nb)	6	5
	F_3 (b)	5	5
	F_3 (nb)	3	2
	F_4 (b)	2	1
	F_4 (nb)	≤ 1	≤ 1
DMC	$B\flat_2$ (b)	8	8
	$B\flat_2$ (nb)	5	5
	F_3 (b)	7	7
	F_3 (nb)	3	4
	$B\flat_3$ (b)	6	6
	$B\flat_3$ (nb)	3	4

Table 4.2: *Estimates of the maximum distance (in mm) the top lip travels (over one cycle) in both the horizontal (z) and vertical (y) directions for non-brassy (nb) and brassy (b) playing. Results from all three musicians are shown. All distances are accurate to approximately* $\pm 1mm$

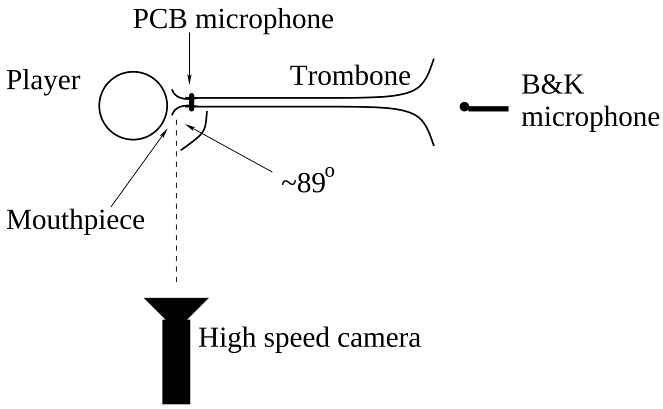


Figure 4.24: *A schematic of the experimental setup for 'sideways' ($y - z$ plane) filming, as seen from above.*

4.8.1 Description of the motion

It is immediately clear from the footage that during playing the lips perform a complex motion in all three dimensions. However, it appears that in all cases it is the top lip which performs the most dramatic behaviour. If we pick a point on the centre of the top lip and follow it across the course of a cycle then it first protrudes 'into' the mouthpiece in the direction of the airflow before arcing 'upwards' towards the roof of the mouthpiece. It then moves 'back' towards the face of the player whilst travelling 'down' towards its initial vertical position. That is, it traces out an elliptical path in the mouthpiece in agreement with the results of Copley and Strong [1996]. Figures 4.29 and 4.30 show the time-evolution of the outline of the lip for the notes $B\flat_2$ and $B\flat_1$ as played by player JG. These four sets of data simplify the process of trying to visualise the motion of the lips during a complete cycle.

Figure 4.31 shows how far the top lip moves in both the direction of airflow (z) and in the vertical (y) direction during one cycle of motion for both *mf* (4.31(a)) and *ffff* (4.31(b)) playing for the note $B\flat_2$, player JG. In the *mf* case,

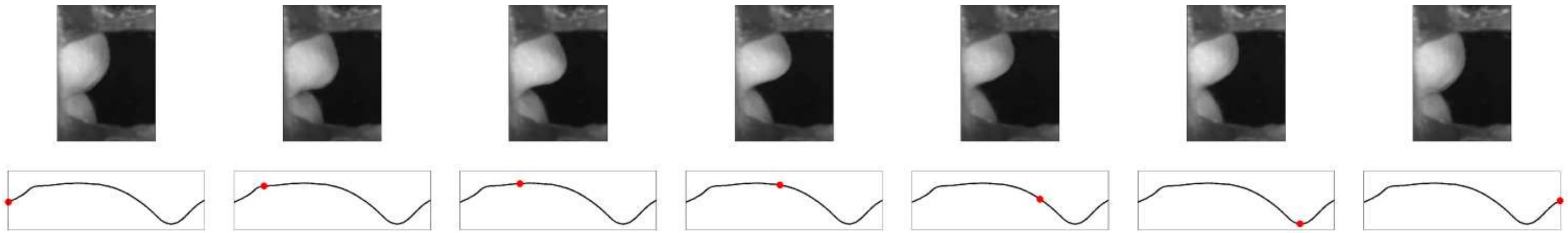


Figure 4.25: *A complete cycle of the lip motion for the note* **B$\flat_2$** ***played at*** **mf** ***by player JG*** *as seen from the side. The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

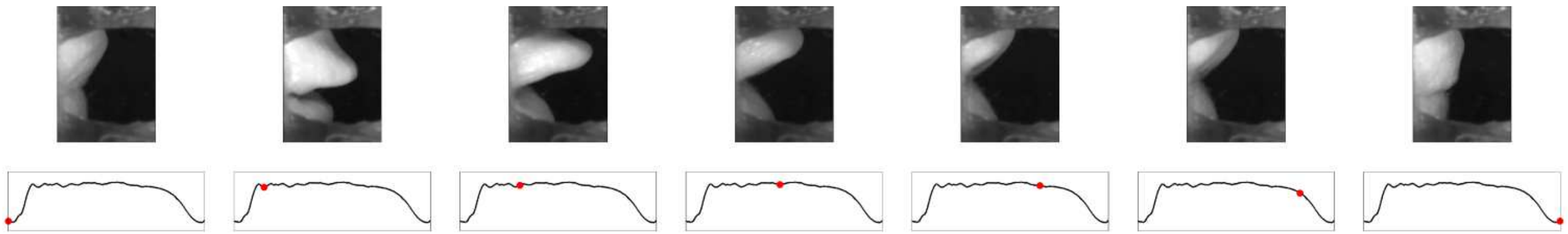


Figure 4.26: *A complete cycle of the lip motion for the note* **B$\flat_2$** ***played at*** **ffff** ***by player JG*** *as seen from the side. The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

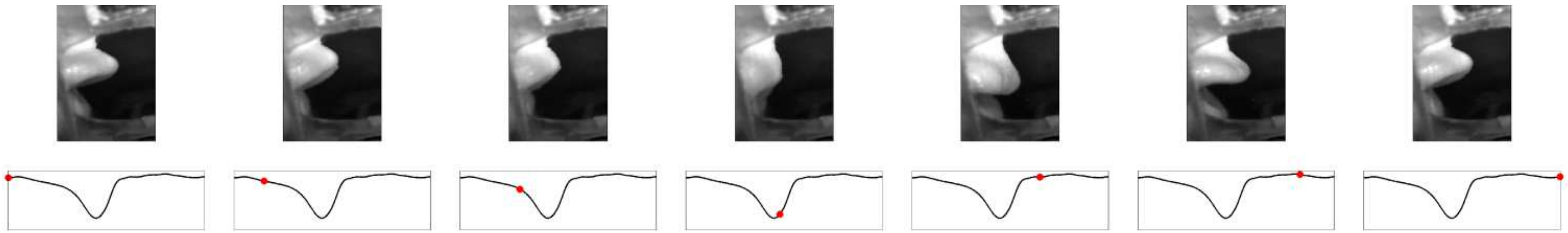


Figure 4.27: *A complete cycle of the lip motion for the note* $\mathbf{B\flat_2}$ ***played at* mf *by player MF*** *as seen from the side. The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

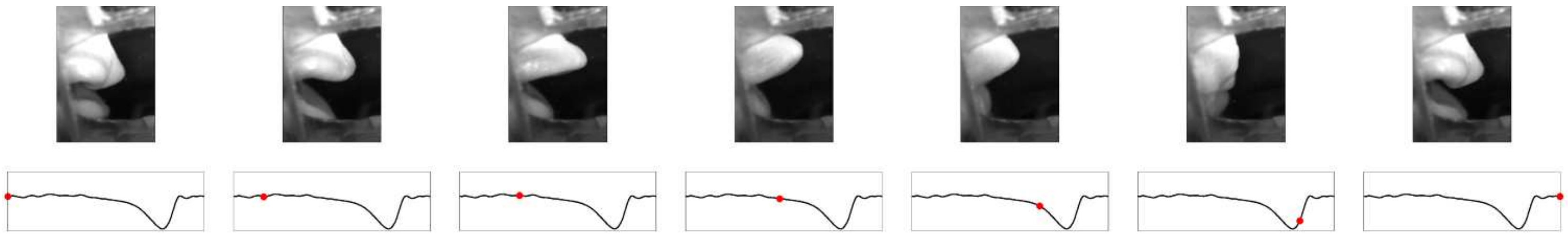


Figure 4.28: *A complete cycle of the lip motion for the note* $\mathbf{B\flat_2}$ ***played at* ffff *by player MF*** *as seen from the side. The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

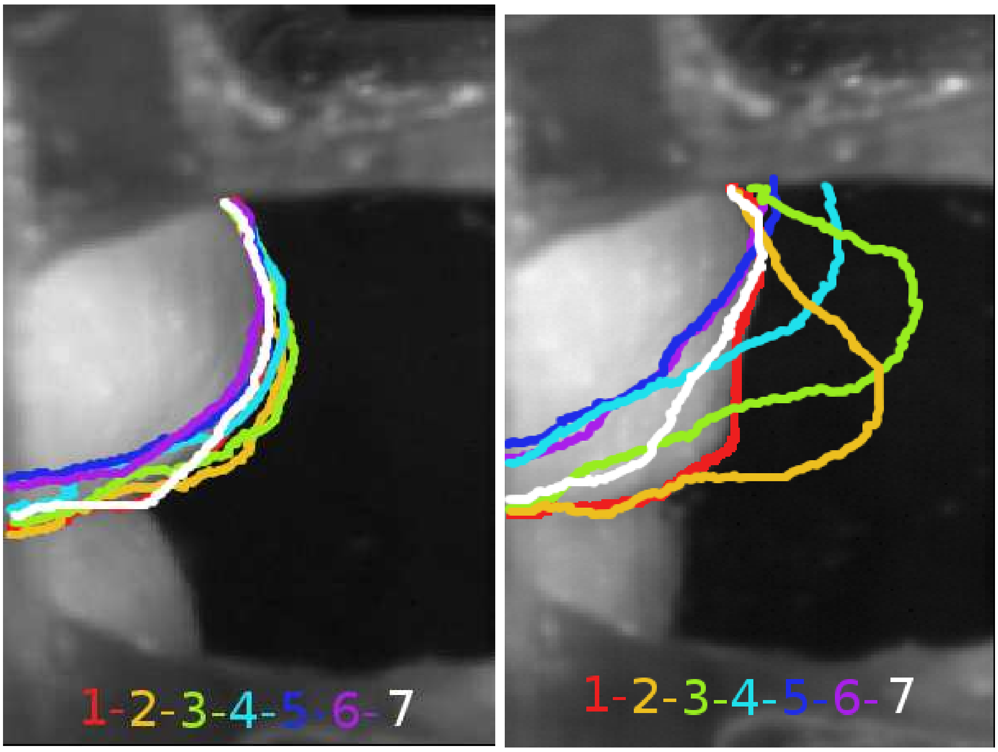


Figure 4.29: *Two figures showing the time evolution of the top lip for non-brassy (left) and brassy (right) playing. Note B♭$_2$, player JG. The coloured line shows the outline of the top lip at various stages in the cycle. The order through the cycle is red, orange, green, turquoise, blue, purple, white*

the maximum horizontal distance moved by the lip is approximately 5 mm, and in the vertical it is 6 mm. In the *ffff* case, the lip moves almost twice as far, with horizontal and vertical distances of 9 and 10 mm. This is in agreement with the lip opening area results, where the amplitude of the motion increased with amplitude.

Table 4.2 collects the (approximate) maximum horizontal and vertical displacements during one cycle of the top lip for all of the notes played by the three musicians; JG, MF, and DMC. Tracking an individual point on the lip over a whole cycle was difficult, and as such the values are accurate to only ± 1 mm. In all cases, the horizontal distance travelled is within 1 mm of the vertical distance travelled within the same cycle. Additionally, as expected the amplitude of the motion increases with amplitude and decreases with pitch.

So, can this dramatic motion of the lip account for the brassy sound at *ffff* level? Comparing the *non-brassy* lip motion for the pedal note ($B\flat_1$) as played by JG and MF (see table 4.2 and figure A.5) with the *brassy* lip motion of the notes F_3 and F_4 as played by the same players, as well as player DMC, we see that the distance travelled by the lip is larger (in some cases, considerably larger) in the case of the non-brassy low note than it is in the brassy higher notes. Comparing the left hand side of figure 4.30 with the right hand side of figure 4.29 should reinforce this idea. Since the low note was audibly non-brassy and the higher ones played as loudly as possible it seems very unlikely, in the light of these data, that the motion of the lips can account for the brassy sound.

4.8.2 Constraint of the lips

It should be noted that the grey area at the top and bottom of the sideways lip motion images is not the edge of the mouthpiece, but is the edge of the optical glass window. When the lips appear to 'disappear' behind this edge they are not necessarily coming into contact with the walls of the mouthpiece. Figure 4.32 shows the relationship between the edge of the window and the internal walls of the mouthpiece. Re-examining figure 4.22 puts this information further in context. With this in mind, there does not seem to be any evidence of constraint of the lips by the mouthpiece at any point for any playing dynamic. This suggests that it is not a constraint of the lips by the mouthpiece which is a primary cause of the brassy sound.

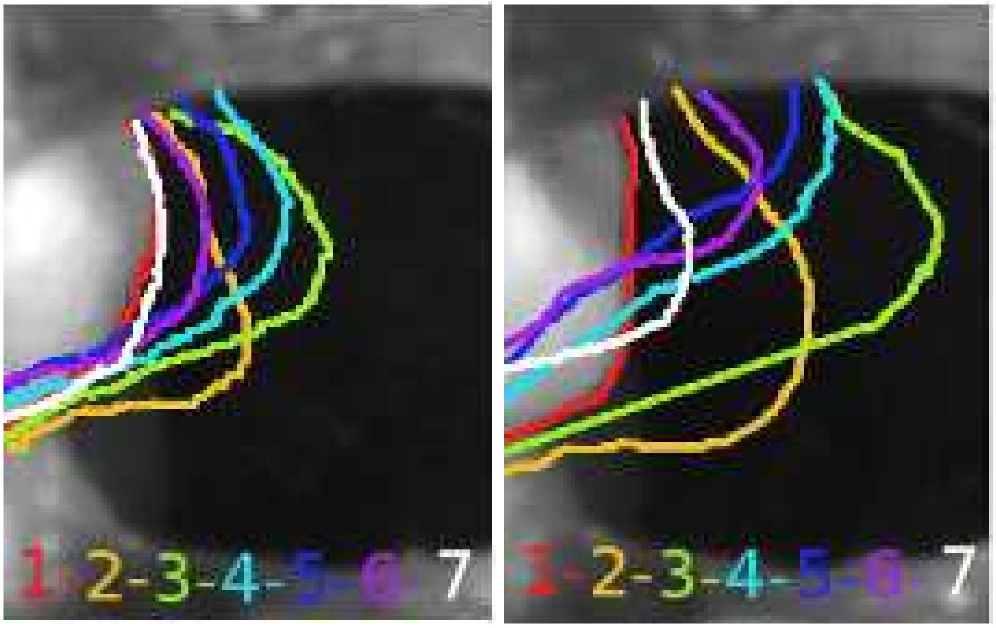
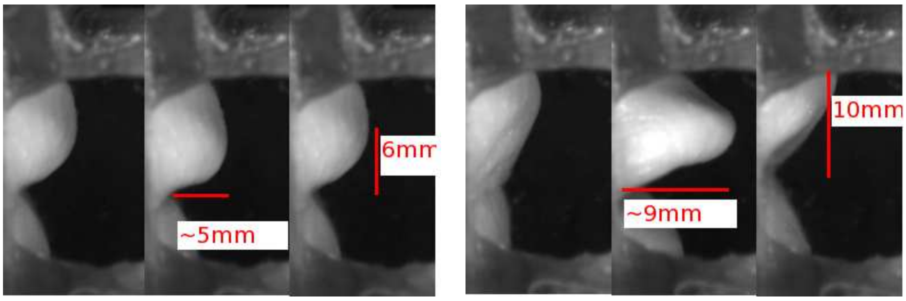


Figure 4.30: *Two figures showing the time evolution of the top lip for non-brassy (left) and brassy (right) playing. Note B$\flat_1$, player JG. The coloured line shows the outline of the top lip at various stages in the cycle. The order through the cycle is red, orange, green, turquoise, blue, purple, white*

4.8.3 Extra volume flow

It is clear from figures 4.25 to 4.28 and A.1 to A.6 that a significant portion of the lip 'wobbles' in the mouthpiece during the middle of the cycle, when the lip is furthest from its 'fully closed' position. One might expect that this motion would cause a significant volume flow in the mouthpiece. However, on examination of the corresponding pressure signals, we see that in the middle of the cycle, when the largest part of the lip is moving, the pressure in the mouthpiece is almost constant. In fact, the pressure in the mouthpiece appears to be controlled purely by the opening and closing parts of the lip motion. This is further supported by the success of lip models using only one or two degrees of freedom. If this motion were of large significance we would not



(a) non-brassy (b) brassy

Figure 4.31: *Estimates of how far the lip travels in both the horizontal (z) and vertical (y) directions for non-brassy (4.31(a) and brassy (4.31(b)) playing. The three images show how far the lip moves in the horizontal (middle) and vertical (right) directions from the 'fully closed' position (left). These images correspond to images* $1, 3, 5$ *from the cycle in figures 4.25 and 4.26. Player JG, note* $B\flat_2$

expect models which did not incorporate it to produce realistic results.

Accordingly, we can conclude that whilst the motion of the lips during both *mf* and *ffff* playing is extremely complicated, by far the most significant features of the motion are those which govern the lip opening, and hence the volume flow. Once the lips have opened (or closed) the large motion of the extremities of the lips does not appear to have a significant effect on the sound that is produced.

4.8.4 Wider angle filming

For the final part of the experiments with 'sideways' filming the camera was rotated around to approximately 55°, as can be seen in figure 4.33. This meant that it was possible to see some aspects of the opening area ($x - y$) and some of the sideways motion ($y - z$) at the same time. Figures 4.34 and 4.35 show a complete cycle of the lip motion—along with mouthpiece pressure—for both *mf* and *ffff* playing of the note $B\flat_2$, player MF.

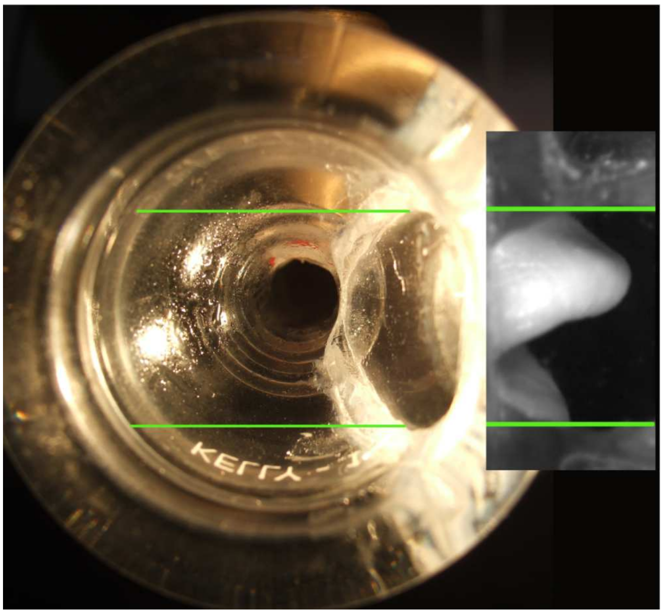


Figure 4.32: *Looking 'into' the mouthpiece with side window. The edge of the lip image (shown in green) corresponds to the edges of the optical window, not the edge of the mouthpiece*

These images make it possible to gain a qualitative understanding of the full motion of the lips during brass instrument playing in a manner that is not possible by examining only 'front' or 'sideways' photography. It can be seen that in both *mf* and *ffff* playing the outer parts of the lips undergo a particularly complicated motion. It appears that the centre and the sides of the top lip are out of phase with each other; the top lip is moving upwards whilst the sides move down, and *vice-versa*. Trying to incorporate the full motion of the lips into a physical model would seem to be particularly difficult. However, it can also be seen that the lip opening area behaves in approximately the same way for both playing dynamics. Since the opening area controls the air flow into the instrument then it is not necessarily a requirement of a simulation to reproduce the full three-dimensional lip motion. A model that captures the main features of the lip should be satisfactory in producing a realistic model.

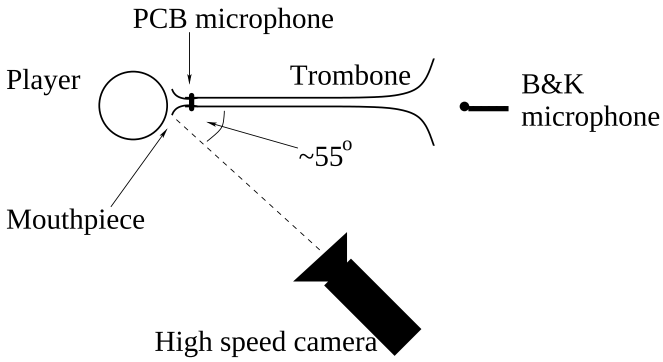


Figure 4.33: *A schematic of the experimental setup for 'sideways' filming at a wider angle, as seen from above*

4.8.5 Comparison with earlier work

Newton [2008] was able to observe the motion of a pair of artificial lips as viewed from the side. He found that a point on the outer edge of his model travelled in an approximately elliptical shape. This is in agreement with the results presented here, and also of Copley and Strong [1996]. He was also able to use MATLAB to track a small dot that was painted onto the lip. Adapting his method for use on human players would allow a more qualitative analysis of motion in the $y - z$ plane than has been possible here.

In a study of flute control parameters, Fabre *et al.* [2008] used a mirror to capture both the 'straight on' and 'sideways' behaviour of the lips at the same time. It would perhaps be of benefit to perform a similar experiment with the lips of brass players. However, this may be difficult to perform because of the small size of most brass instrument mouthpieces.

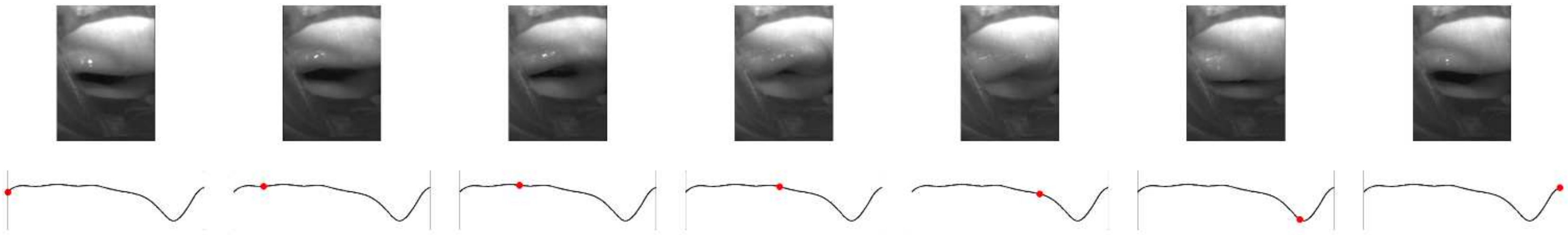


Figure 4.34: *A complete cycle of the lip motion for the note B$\flat_2$* ***played at*** **mf** ***by player MF*** *filmed from an angle of approximately* 55°. *The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

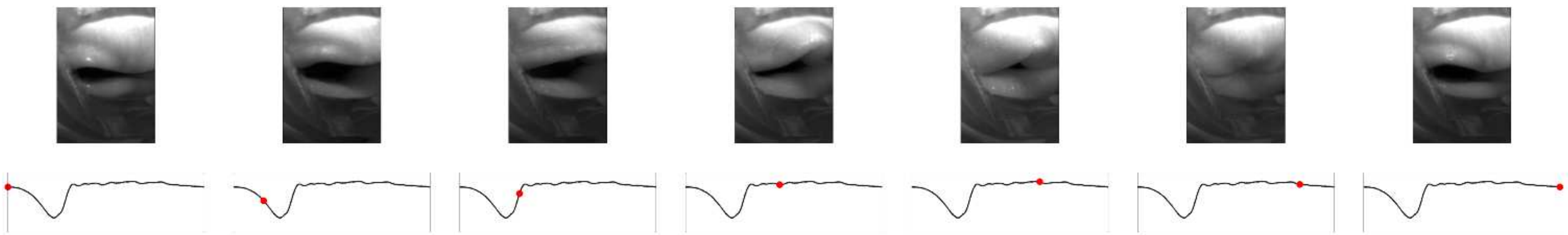


Figure 4.35: *A complete cycle of the lip motion for the note B$\flat_2$* ***played at*** **ffff** ***by player MF*** *filmed from an angle of approximately* 55°. *The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

4.9 Brassy playing: using an artificial mouth

An attempt was made to use the artificial mouth (see section 3.5) as a way of exciting an instrument at a brassy level. Unfortunately this proved unsuccessful. Firstly, the air compressor used was not capable of producing a suitably high pressure in the 'mouth' in order to produce a suitably loud sound. The Air Control Industries Ltd 8MS11 0.25kW air pump that was used could only produce a maximum pressure of around 1kPa. Examining the typical mouthpiece pressures of human players suggests that a value of several kPa is required to produce a significantly brass sound. However, switching to a different, more powerful, source of compressed air was also not sufficient to produce a brassy sound on the artificial mouth. The artificial mouth is designed such that once a playable embouchure has been found, it will remain permanently in that embouchure. When a human musician wishes to change from non-brassy to brassy, they do more than just 'blow harder'. They also change the shape and tension of their lips in order to form an embouchure suitable to maintain a self-sustained oscillation at the loudest amplitudes. During a crescendo they continually make adjustments in order to maintain the oscillation.

Currently, if a stable regime of oscillation is obtained using the artificial mouth and the pressure subsequently increased then it is not possible to adjust the embouchure to maintain the oscillation. Instead, the sound becomes 'airier' until the oscillation collapses—the lips continue to vibrate, but they do not do so in a musical manner: the sound heard is that of the lips striking one another whilst air is forced between them (a child would perhaps describe such a sound as a 'raspberry'). In order to successfully obtain a brassy sound using the artificial mouth it will be necessary to modify the design in order to allow modification of the embouchure quickly and easily. In order to produce a realistic *crescendo* using the artificial mouth a way of controlling and altering the embouchure smoothly during playing must be found.

4.10 Brassy playing: conclusions

Recordings of the pressure in the mouthpiece of a tenor trombone and a horn during brassy and non-brassy playing were made using a low sensitivity microphone. Results were consistent between players, instruments, and pitches. As expected, the only significant change between brassy and non-brassy playing was the maximum rate of change of mouthpiece pressure. This is in agreement with the results of Hirschberg *et al.* [1996].

The form of the corresponding external pressure signals, however, changed greatly with dynamic level. In the case of extremely loud playing there is clear evidence of shockwave formation within the body of the instrument. Calculation of the spectral centroid of both mouthpiece and radiated pressures reinforces this conclusion.

The lip opening area was measured using a high speed video camera for all of the players and instruments. The opening area increased in amplitude for louder playing dynamic and decreased with increasing pitch. These variations are to be expected. There were no unusual features of the lip motion at any playing level and no evidence of lip saturation or constriction. It therefore has to be concluded that the brassy sound is not generated by a change in the motion of the lips during extremely loud playing.

A new trombone mouthpiece with side window was used to record the motion of the lips in the $y - z$ plane for both brassy and non-brassy playing. The top lip performs a more complicated motion than the bottom lip. Analysis shows that the top lip travels an approximately elliptical path and protrudes into the mouthpiece as far as 1cm in both y and z directions. Motion of the lip in this plane does not appear to contribute significantly to the creation of the brassy timbre.

Chapter 5

The behaviour of the lip reed during the starting transient

''Begin at the beginning', the King said, very gravely, 'and go on till you come to the end: then stop''

—ALICE'S ADVENTURES IN WONDERLAND

5.1 The starting transient

One sound that will be familiar to any student of the brass wind instruments is the 'fluffed' or 'split' note, where the musician fails to achieve a clean attack on the note chosen. Brass musicians spend many hours learning to consistently 'hit' the correct note [Chick, 2009] and the ease with which a note can be started on a particular instrument is often used by musicians as an indicator of instrument quality. In addition, the starting transient is of great importance in determining the character of an instrument, as established by Luce and Clark [1967] in their classic study of brass instrument tones. It is also known that the starting transient is required by the listener in order to differentiate between the sounds made by two different instruments [Grey and Moorer, 1977]. In short, the starting transient of a note is of critical importance to both the brass musician and to the listener. However, there have been very few publications of research into the starting transients of the brass wind instruments. The work presented here is a continuation of some preliminary studies performed by Bromage [2007] at the University of Edinburgh.

A typical starting transient on a brass wind instrument has a duration of approximately 50ms. The work here examines the relationship between the motion of the lips of the player, the pressure in the mouthpiece of the instrument and the sound as heard by the listener during the first 100ms of the sounding of a note on a number of different brass instruments.

5.2 Starting transients: theory

A brass instrument tone is initiated by a periodic opening and closing of the player's lips. The frequency of this initial lip vibration is controlled by the player's choice of embouchure, which determines the mechanical resonance behaviour of the lips. The pressure pulse created by the first cycle of opening and closing propagates to the bell of the instrument, where some of the sound is radiated into the atmosphere and some is reflected back down the instrument.

If the player has initiated the lip vibrations at the correct frequency the reflected sound should arrive with the appropriate phase to reinforce the lip vibrations. If the reflected wave is sufficiently out of phase with the player's lips it is possible that the note will be 'split' and that—albeit, very briefly—the wrong note will sound. Less disastrous mismatches of phase may be responsible for modifications of the transient waveform, such as the amplitude 'blips' reported by Luce and Clark [1967].

It is characteristic of notes played on orchestral brass instruments that the lip resonance frequency is normally close to a high number mode of the air column. For example, when the note F_3 is played on a horn in $B\flat$-basso, the lip frequency is close to the sixth mode of the air column. This means that the time taken for the initial disturbance to propagate down the tube and return to the lips is approximately six times the period of the note. Only after the first six cycles of the lips can the acoustic resonance of the tube couple with the lips to establish a stable regime of oscillation locked to the air column mode frequency.

For players of long coiled or folded brass instruments, such as the horn, the radiated sound from the bell can reach the player's ear before the reflected pressure wave returns back along the instrument to the mouthpiece. It is not currently known whether this time delay between the auditory and acoustic feedback signals has a significant effect on the player's control of the starting transient.

5.3 Starting transients: experimental setup

The following sections describe the experimental apparatus and procedure used for experiments on the starting transient.

5.3.1 Instruments

Three instruments were used for the experiments described in this part of the thesis: a natural horn, a tenor trombone, and a bass trombone. These instruments were chosen because they allow the musician to sound the same pitch on the same instrument in multiple ways. That is, the same pitch may be sounded but using different lengths of tubing. For the experiments using trombones, the instrument length was altered by adjusting the instrument slide and/or trigger mechanism whilst the length of the horn was changed by the use of two different crooks; $B\flat$-alto (2.7m horn) and $B\flat$-basso (5.6m) respectively. The natural horn and crooks used can be seen in figure 5.1. Six different musicians were asked to participate: three horn players, two tenor trombonists and one bass trombonist. This meant that it was possible to compare features across both different performers and different instruments playing the same note. As in the rest of the thesis, all the musicians were either professionals or skilled amateurs with many years orchestral experience.

Three different pitches were chosen: F_3, $B\flat_3$, and $B\flat_4$. These were selected as being comfortable to play in different ways on all three instruments. The experiments were repeated with several different players on each instrument in order to identify common features. Some measurements were also made of the note $B\flat_2$ on the bass trombone.

5.4 Experimental setup

In order to gain optical access to the lips, the transparent trombone and horn mouthpieces detailed in section 3.1.1 were again put to use. The Phantom v4.1 camera and Schott KL1500 light source (see section 3.1) were used to record the motion of the lips.

A hole was drilled into the side of the trombone mouthpiece and a PCB 106B microphone inserted such that the diaphragm was flush with the inside wall

Figure 5.1: *The natural horn used for experiments on the starting transient. This instrument has no valves. Instead, the length of the instrument can be altered by the use of crooks of different lengths. The two crooks pictured here are a B♭-alto crook (a* $2.7m$ *long horn) and a longer B♭-basso crook (*$5.6m$ *long horn)*

of the mouthpiece. Since the dimensions of the horn mouthpiece are smaller than that of the microphone, a smaller diameter hole was drilled and a short probe attachment used to connect the 106B to the mouthpiece. The sound radiated from the bell of each instrument was recorded using a Brüel and Kjær 4192 microphone. Both the PCB and Brüel and Kjær microphones were once again connected to the PULSE acquisition hardware (see section 4.4.2). The experimental setups for the trombone can be seen in figure 5.2.

In order to successfully determine the relationship between the motion of the lips, the pressure in the mouthpiece, and the sound heard by the listener during the starting transient it was essential that all three signals were correctly synchronised. This synchronisation was performed using the process outlined

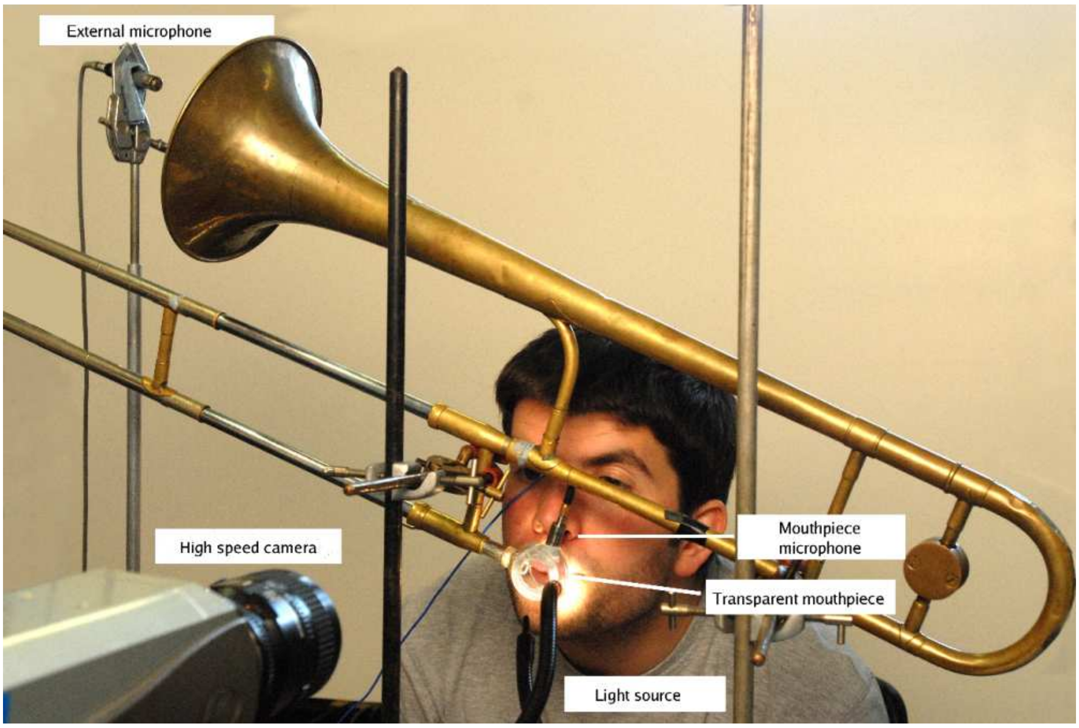


Figure 5.2: *The experimental setup for measurements of the starting transient on a trombone. The motion of the lips was captured by the high speed camera, whilst the pressure in the mouthpiece and radiated sound were simultaneously recorded.*

in section 5.4.1.

5.4.1 Starting transients: synchronisation

The capture process on the high speed camera was triggered using a BNC Model 500 Pulse Generator. The signal from this generator was simultaneously used to trigger the recording of the mouthpiece and radiated sound pressures by the PULSE acquisition hardware. The trigger signal itself was also recorded by PULSE. Both PULSE and the high speed camera were configured to use 'pre-trigger' in order to simplify the experimental process. In order to clarify this fully, it is necessary to explain how the high speed camera works.

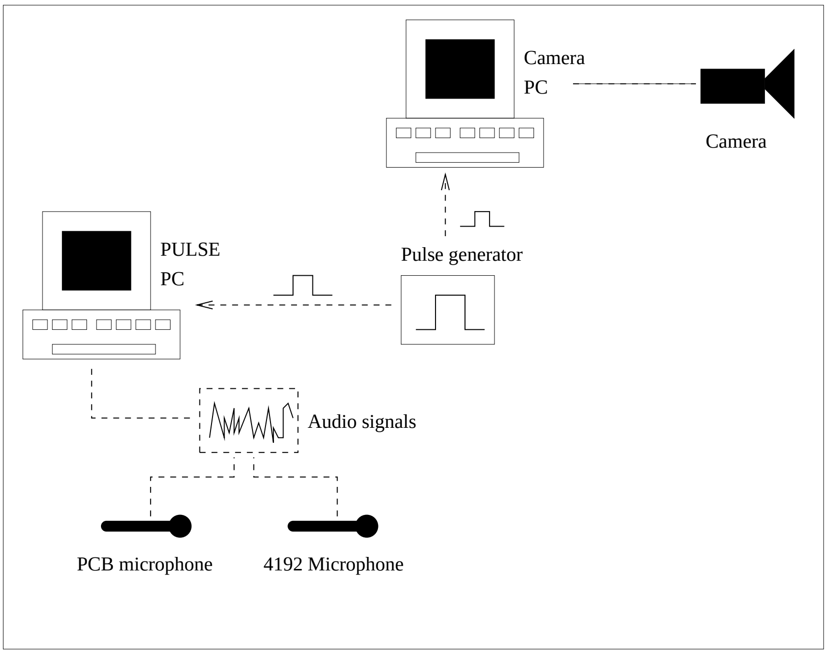


Figure 5.3: *The synchronisation process for experiments on the starting transient. The high speed camera and audio signals were synchronised by using a pulse generator to trigger the capture process. The trigger signal was also recorded to facilitate the synchronisation*

5.4.2 The Phantom v4.1 camera

The Phantom v4.1 camera is controlled by a PC with the Phantom camera software installed on it, to which it is connected via firewire. The rate of data communication between PC and camera is not fast enough to allow recordings to be saved directly on to the computer hard drive. Instead, the camera has a buffer which it uses to temporarily store the video that it captures. The buffer has a limited size and so, at the frame rates and resolutions used in the thesis (typically 5000 frames per second at 256x128 pixels) it cannot capture more than approximately 1.2s of footage.

Since the capture time of the camera is limited in this fashion, it was not practical to trigger a recording and *then* ask the musician to begin playing.

However, one feature of the camera is that it continually captures the video signal, and then overwrites the buffer as necessary. So, there is, in effect, always 1.2s worth of video stored on the camera. 1.2s after the recording is triggered, the camera stops writing to the buffer and saves the data which is stored. This data can then be saved onto the hard drive of the control PC.

Using the pre-trigger function, however, the user can control how much of the signal is saved *before* the trigger is activated. Set the pre-trigger to 0.3s, for example, and 0.3s of the data recorded before the trigger will be kept whilst the camera then records for another 0.9s after receiving the trigger signal, for a total recording time of 1.2s.

The PULSE data acquisition software can be configured in a similar way. It was decided that a pre-trigger time of 0.5s would be used on the audio recordings whilst the camera was set to a pre-trigger time of, typically, 0.4s. Unfortunately, the camera software quantises the allowed pre-trigger times depending on the resolution and frame rate chosen, and so an appropriate pre-trigger had to be chosen for each configuration. The total audio capture time of PULSE was chosen such that the total length of audio signal captured was always longer than the total video capture time in order to ensure that no data was lost.

5.4.3 The recording process

In practice, an experimental measurement ran as follows:

1. The apparatus was set up, light source adjusted and camera focused to obtain a clear image using the camera preview.

2. A suitable pre-trigger time was set using the camera software based on the resolution and frame rate required.

3. The musician began playing the desired note.

4. As soon as the experimentalist heard the start of the note,the capture process was triggered manually using the BNC Model 500 Pulse Generator. As long as the experimentalist reacted within the pre-trigger time of the camera then all of the starting transient was captured on both camera and PULSE computer.

Since the trigger signal was captured by PULSE—and the pre-trigger times of both audio signals and high speed camera controlled—it was then a simple process to identify at which point in the audio signal the camera was triggered and thus to synchronise all three sets of data. This synchronisation process was carried out using MATLAB.

5.5 Starting transients: analysis procedure

The high speed camera footage was once again split into individual frames and the 'binarisation' process detailed in section 3.2.1 applied in order to extract the relevant lip opening area information. These data were then synchronised with the audio signals taken during the experimental procedure. All three data sets were then imported into MATLAB for processing and analysis.

5.5.1 Instantaneous lip opening area 'frequency', $\overline{\nu}$

As a brass musician starts to play a note, he (or she) must cause his lips to vibrate at some initial frequency which matches the frequency of the note that they are aiming to produce. In order to examine how effective the musicians were in this respect the 'instantaneous' lip opening area frequency was calculated for each data set, as explained below.

It is expected that the time period that it takes for the lips to open and close again will vary during the starting transient. If no two cycles of motion are identical then the lip opening area will not be a periodic quantity. Is it possible to assign a 'frequency' to a non-periodic signal? However, noting the fact that each cycle of the motion has an easily identifiable point—that of maximum lip opening area—then we can define a 'pseudo-frequency' for an individual cycle. Measuring the time period between successive maxima of lip opening area and taking the reciprocal yields a quantity measured in s^{-1} (Hz) , which we shall make use of, and call the 'instantaneous' lip opening area frequency, $\overline{\nu}$. A common technique in signal analysis is to use the rate of change of phase as a way of calculating an instantaneous frequency, however this is a rather more complicated method than is necessary here.

In order to calculate $\overline{\nu}$ accurately, a MATLAB script was written that could detect local maxima in the opening area data. The time period between peaks could then be calculated and $\overline{\nu}$ found. However, the accuracy of this process was limited by the sample rate of the Phantom v4.1 high speed camera. In order to remove unwanted quantisation effects (an artifact of aliasing) and improve the accuracy of the calculation, the opening area data was re-sampled (increased) using an anti-aliasing (low pass) FIR filter. The filter uses n points on either side of the current sample in order to perform a linear fit using a least-squares method. In order to maximise the accuracy of the resampling process n was set to 10. To ensure that the re-sampling did not significantly alter the data, a careful examination of the original video footage, in comparison with both the original and re-sampled lip opening area data, was made. It was found that it was possible to increase the sampling rate of the data by a factor of five without removing any significant information. At this increased sample rate the aliasing effect was greatly reduced and so a satisfactory calculation of $\overline{v}$ could be made. The re-sampling process and calculation of $\overline{v}$ are shown in figures 5.4 and 5.5. The accuracy of the re-sampling process can be seen by comparing the overlap between the raw (blue) and re-sampled (green) data points.

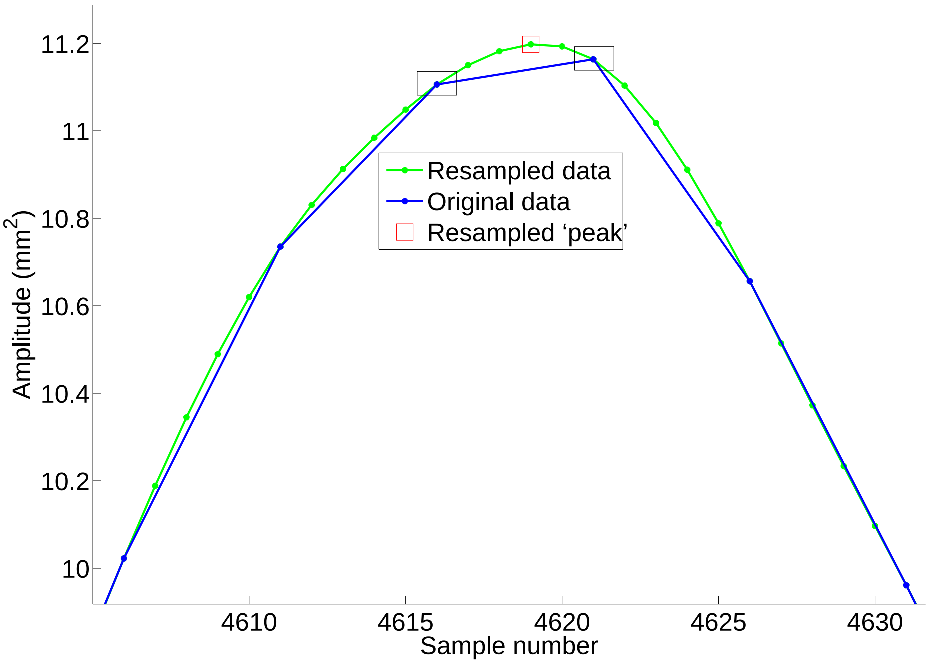


Figure 5.4: *At the original frame rate of the camera, the peak detector could find only one of the original data points (marked with a black rectangle). The location of these points relative to the 'true' peak caused unwanted quantisation effects. Re-sampling the data (green line) allowed a more accurate approximation to the 'true' peak to be made (red rectangle)*

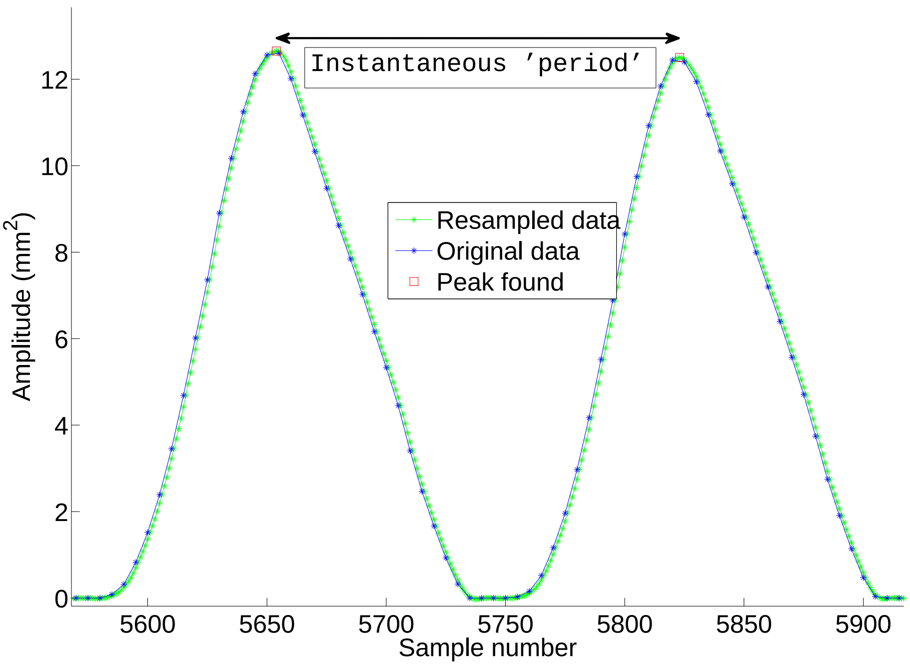


Figure 5.5: *The re-sampling process did not change the form of the data significantly, even when re-sampled by a factor five*

5.6 Starting transient: results

Acoustic Pulse Reflectometry (APR) is an experimental technique which can be used to deduce some of the physical properties of a brass instrument. An acoustic pulse is injected into the instrument via loudspeaker and any reflections recorded using several microphones. Comparing the reflections to the initial impulse makes it possible to calculate the internal bore profile of the instrument, calculate the acoustic impedance, or even detect leaks [Kemp, 2002]. Here, however, we are concerned only with determining how long it takes for an acoustic pulse to travel the length of an instrument and return to the mouthpiece.

The first instrument used in this part of the thesis was a 5.6m long natural

Figure 5.6: *Reflection function of a* 5.6m *long horn in B♭-basso, measured using an acoustic pulse reflectometer. It can be seen clearly that the time taken for the first reflection to return to the input of the instrument is* 32ms

horn, using a *B*♭-basso crook. Figure 5.6 shows the reflection function of this instrument measured by APR. It can be seen clearly that it takes approximately 32ms for an acoustic signal to travel the length of the instrument and back again due to the reflection at the bell. Therefore, as a crude approximation, when examining the sound radiated from the 5.6m horn during the starting transient an initial disturbance at the bell is expected 16ms after the start of the note. After 32ms, the amplitude of the pressure signal in the mouthpiece should grow rapidly as the returning wave begins to reinforce the oscillation of the lips.

5.6.1 Note F_3, 5.6m horn in $B\flat$-basso

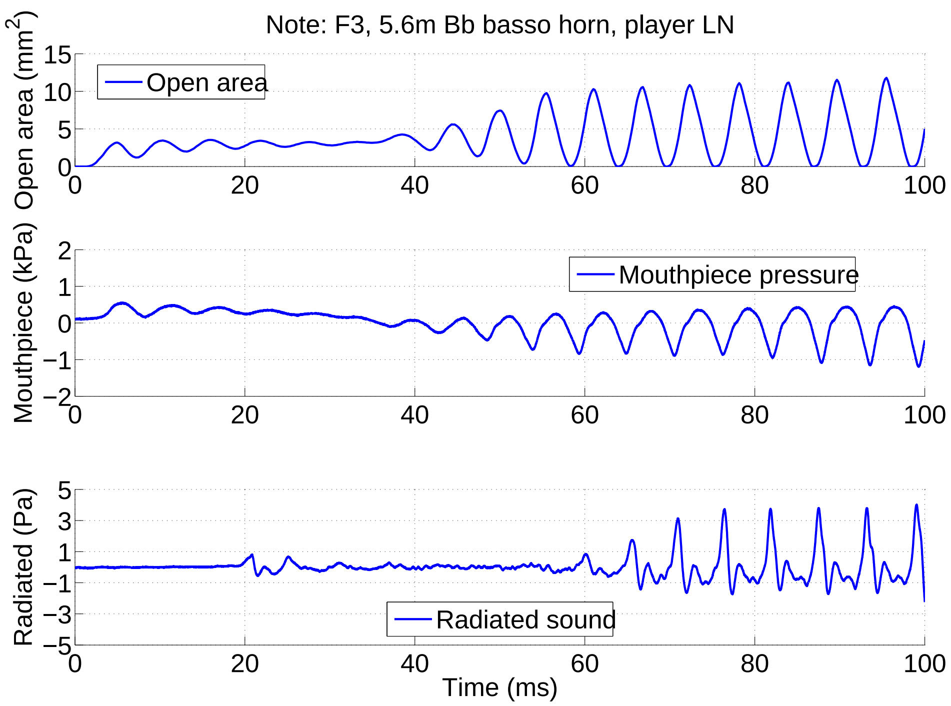


Figure 5.7: *Starting transient for the note F_3 on the* 5.6 *m horn in $B\flat$-basso. The lip opening area, mouthpiece pressure and radiated sound are shown. Player **LN***

Figures 5.7, 5.8 and 5.9 show typical recordings of the starting transient of the note F_3 played on the 5.6 m horn in $B\flat$-basso by three players; LN, JC, and HP. Figure 5.10 displays all three of these data for ease of comparison between the different players.

In all three cases, it can be seen quite clearly that as the lips begin to open, there is an initial pressure rise inside the mouthpiece. At this stage there is, as expected, no sound radiated from the instrument. Approximately 16ms later that there is a 'blip' in the sound radiated from the instrument, as predicted using the information recorded using APR. After 32ms, both lip open area and

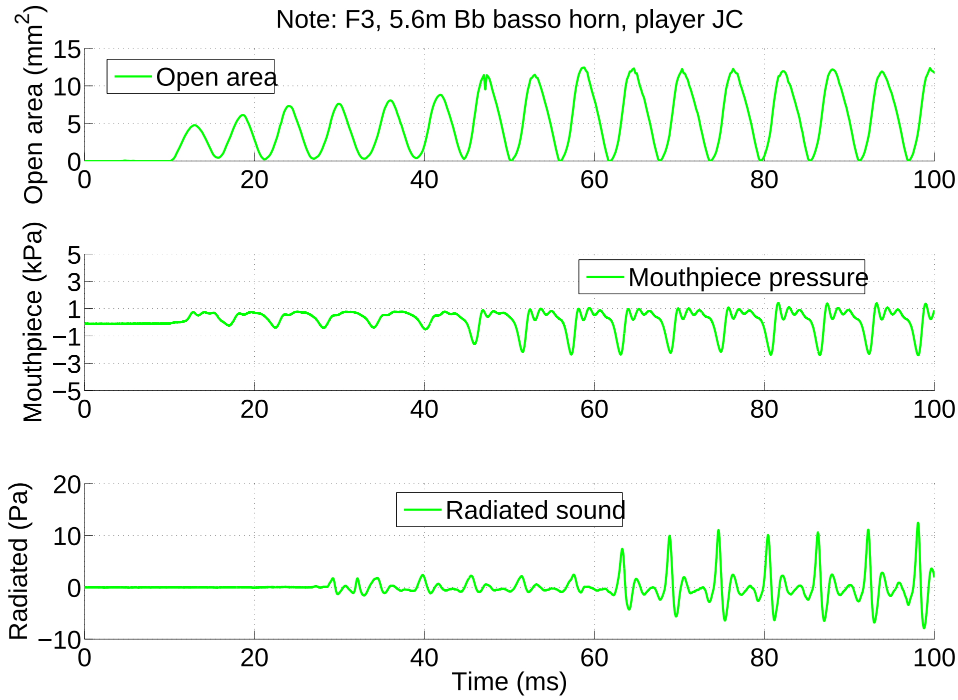


Figure 5.8: *Starting transient for the note F_3 on the* 5.6 *m horn in B♭-basso. The lip opening area, mouthpiece pressure and radiated sound are shown. Player **JC***

mouthpiece pressure grow rapidly in amplitude as the reflections from the bell reach the mouthpiece and reinforce the oscillation. Once these reinforced oscillations reach the bell of the instrument after 48ms the radiated pressure also increases in amplitude. The note F_3 is the sixth mode of the air column for the 5.6m horn and as such it can be seen that there are six cycles of motion before the air column provides feedback to the motion of the lips. These data therefore reinforce our theoretical model of what happens during the starting transient of a note on a brass instrument.

The behaviour of the recording made by player LN is particularly interesting. For the first six cycles of the lip oscillation the amplitude of both lip open area and mouthpiece pressure are extremely small. Once the initial

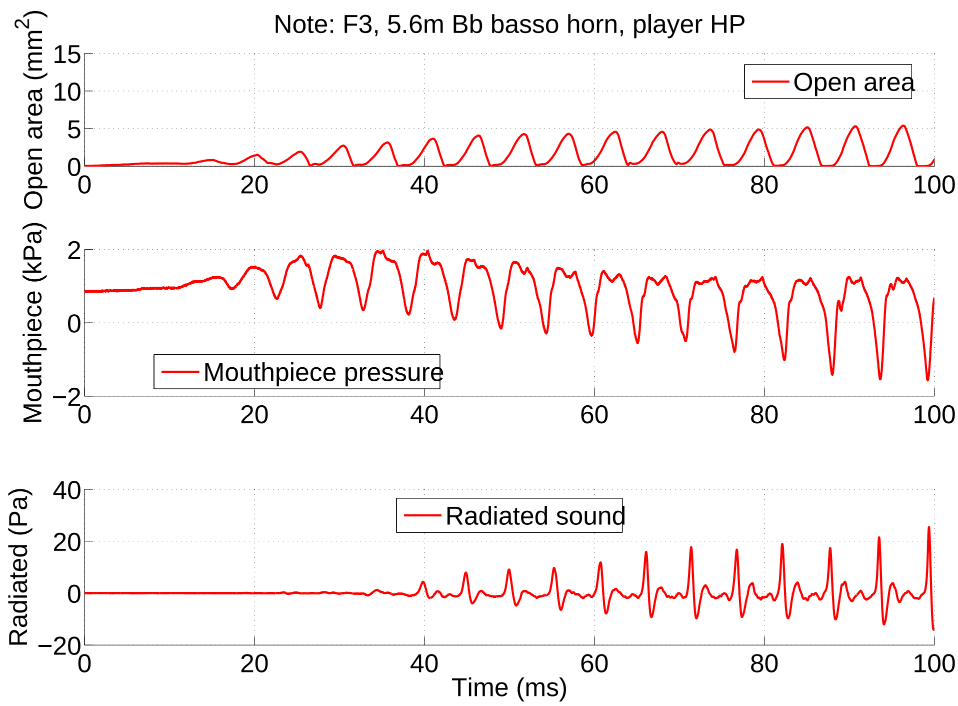


Figure 5.9: *Starting transient for the note* F_3 *on the* 5.6 *m horn in B♭-basso. The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***HP***

pressure pulse reaches the bell of the instrument the radiated sound pressure is also correspondingly small. Once the acoustic feedback begins after 32ms, however, the behaviour is startling, with rapid growth of both open area and mouthpiece pressure. It appears that this particular combination of embouchure and mouth pressure chosen by the player was not capable of sustaining the lip vibration in the absence of feedback from the instrument.

In contrast, the lip vibration of player JC grows in amplitude through the first six cycles of oscillation. Since the instrument, mouthpiece, and pitch are the same in all three cases, variations must be purely due to playing technique. It has been reported that saxophonists are able to tune their vocal tract resonance to support the production of particular notes [Chen *et al.*, 2008].

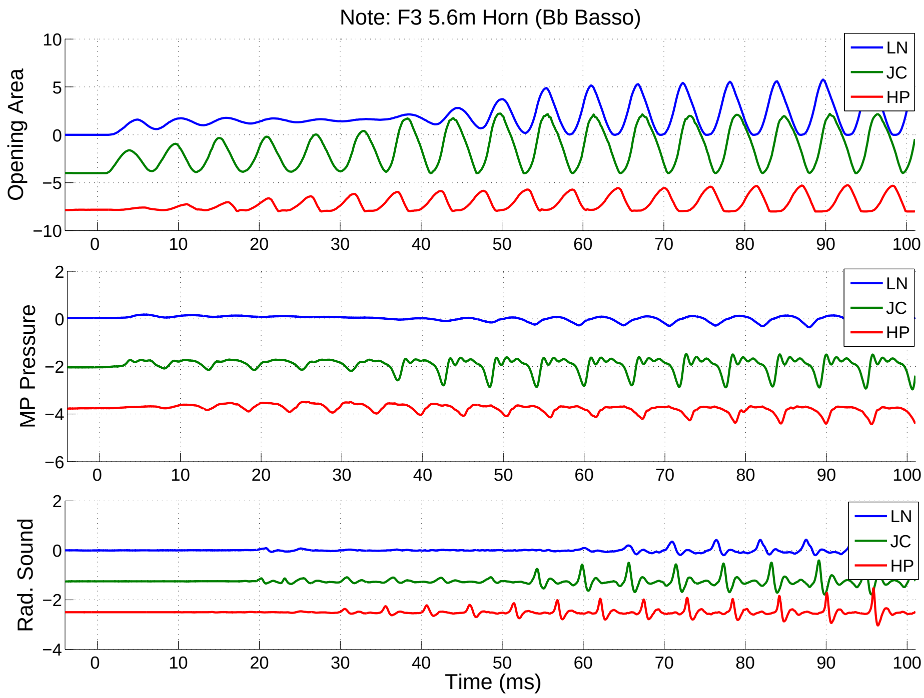


Figure 5.10: *three recordings of the note F3 on the 5.6m horn in B♭-basso, played by three different performers; LN, JC, and HP. The units on the axis are arbitrary and the data have been offset vertically and rescaled in order to facilitate comparison*

It may be that player JC was making use of a similar technique to sustain the oscillation before the acoustical feedback from the instrument began. The signals again grow noticeably in amplitude after 32ms.

Figure 5.9 shows the starting behaviour of the same note as played by player HP. Once more we see that the transient behaviour is much the same of that of players LN and JC—there is a blip in the radiated sound 16ms after the lips begin to open and the amplitude of the lip opening area increases once the first pulse returns to the mouthpiece after 32ms. However, it is also noticeable that the lip open area of player HP is much smaller than that of LN or JC. As mentioned in section 3.4 this player was not entirely comfortable with the

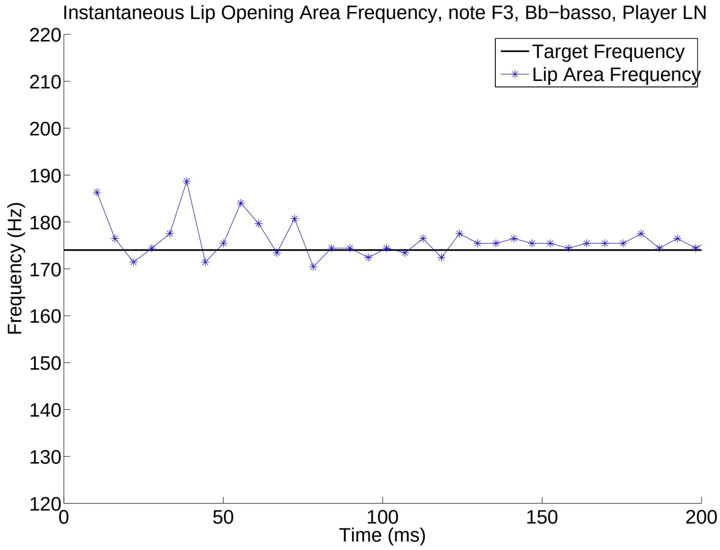


Figure 5.11: *Instantaneous lip opening area frequency ($\overline{\nu}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440$Hz. Note F_3, $B\flat$-basso horn. Player* ***LN***

setup, and so it may be that the experimental conditions were not suitable for extracting the normal behaviour of the lips of player HP.

Figures 5.11, 5.12, and 5.13 contain the calculated instantaneous lip opening area frequencies, $\overline{\nu}$, for the note F_3 as played by players LN, JC, and HP on the 5.6m horn in $B\flat$-basso. It is immediately clear that for each of the three musicians the behaviour of $\overline{\nu}$ during the starting transient is very different. The lip oscillation of player LN begins at a frequency of approximately 187Hz, corresponding to a pitch 125 cents higher than the target frequency of 174Hz ($A = 440$Hz). The lip frequency then decreases rapidly during the next cycle, and the next three cycles are all within 30cents of the target frequency. Suddenly the lip frequency increases rapidly again for one cycle before dropping down below the target frequency. $\overline{\nu}$ continues to oscillate around the target frequency, with the 'amplitude' of each oscillation decreasing

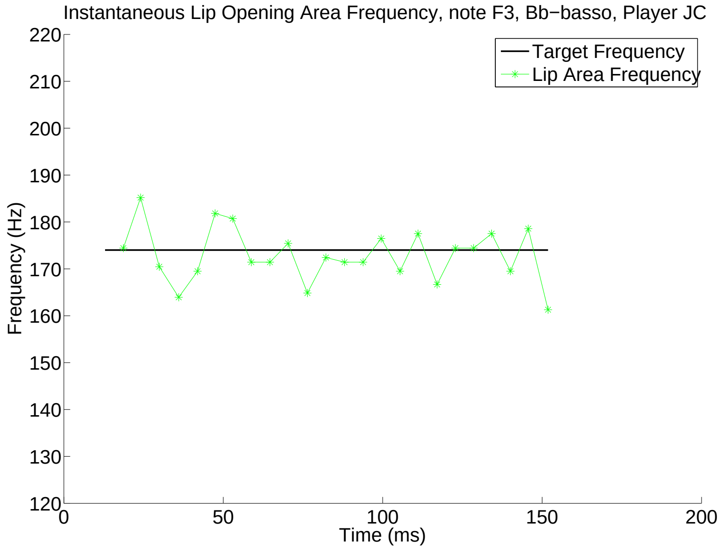


Figure 5.12: *Instantaneous lip opening area frequency ($\overline{\nu}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440$Hz. Note F_3, B♭-basso horn. Player* ***JC***

until around 65ms into the motion where the lip oscillation frequency remains approximately constant. It is interesting to note that whilst there seems to be distinct variation in the value of $\overline{\nu}$ *above* the target frequency there are fewer variations *below* the target. Does the player somehow limit the lowest frequency at which their lips would vibrate? It should also be noted that during the steady state oscillation the instantaneous value of the lip frequency is slightly higher than the target. This may indicate that the instrument was not perfectly tuned to $A = 440$Hz.

Examining the instantaneous lip opening frequency of player JC we see that there are some similarities to that of player LN, but also some differences. JC's initial lip vibration is almost exactly the same as the target frequency. However, the second cycle of oscillation is approximately 10Hz (96 cents) higher than the target. $\overline{\nu}$ then decreases, as in the case of player LN, but in

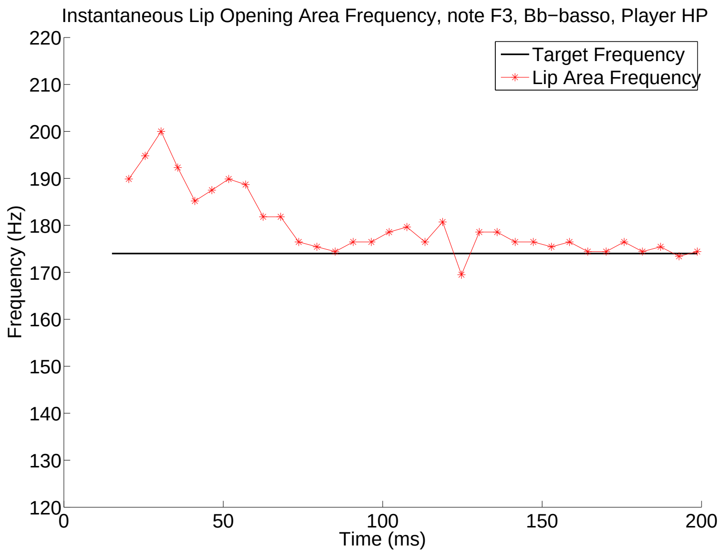


Figure 5.13: *Instantaneous lip opening area frequency ($\overline{v}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note F_3, B♭-basso horn. Player **HP***

this case seems to 'overshoot' the target frequency, again by around 100 cents. The lip frequency then increases well above the target frequency and then continues to oscillate around the target. Interestingly, the 'steady state' part of the motion after around 50ms of the motion does not remain constant as in the case of LN. Instead, the oscillation continues but with a much smaller amplitude than during the initial transient. It can also be seen that the highest values of $\overline{v}$ are lower for JC than LN. However, the lowest values of the same variable are also lower for player JC.

Player HP, finally, demonstrates completely different behaviour to that of either player LN or JC. The lip motion of this player begins at around 190Hz, a full 150 cents above the target frequency, and then *increases* to over 200Hz, 240 cents higher than the note F_3 aimed for. Over the following 50ms the instantaneous lip opening frequency tends to decrease until only slightly higher than the target frequency. It then remains approximately constant at a value 2 or 3Hz higher than the target. Only once during the entire recording does the value of $\overline{\nu}$ drop more than 1Hz below the target frequency.

Comparing and contrasting the behaviour of all three players it is clear that whilst there are many similarities between the different players, there are also many dramatic differences. The question remains, however, as to whether or not these differences are of importance to either the musician or to the listener. Listening purely to the radiated sound suggests that all three notes are satisfactory; there are no ‘splits’ or ‘blips’. It is possible that the behaviour of player LN, where the player is unable to sustain the oscillation without feedback, is not desirable whereas the behaviour of player JC, where the player manages to obtain the correct frequency of vibration and sustain it is an example of good technique. However, it may also be possible that player LN uses the instrument to ‘do the work’ and in so doing uses the lips efficiently whilst player JC has to work harder than is necessary. Similarly, comparing the behaviour of the instantaneous lip opening area frequency for all three players shows three different behaviours. Whilst all players seem to begin their oscillation slightly higher than the target frequency, that is where the similarities end. Player HP has lips that oscillate well above the target frequency whilst LN and JC produce lip opening areas that oscillate around the target pitch. Since all three notes sound satisfactory to the listener it may be that no single method is preferable. Repeat measurements of many players—at many different levels of skill—are required before any firm conclusions can be drawn.

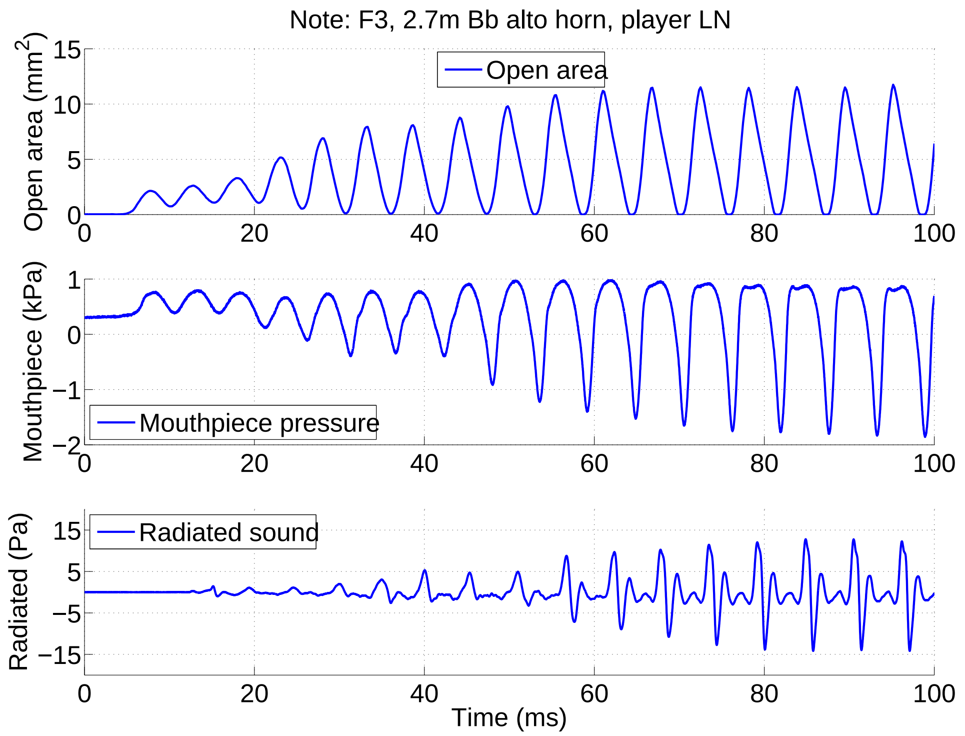


Figure 5.14: *Starting transient for the note F_3 on the 2.7 m horn in B♭-alto. The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***LN***

5.6.2 Note F_3, 2.7m horn in $B\flat$-alto

Figures 5.14, 5.15, 5.16 and show typical recordings for the note F_3 on the 2.7m horn in $B\flat$-alto for players LN, JC, and HP. These data also follow the pattern of initial small amplitude disturbance followed by rapid amplitude growth as the initial disturbance is reflected back to the lip reed. In this case the time for the reflection to return is around 16ms. This behaviour is to be expected for this much shorter instrument. The note F_3 corresponds to the third mode of the air column for the 2.7m horn and we see that there are three cycles of lip motion before the acoustic feedback develops.

Figures 5.17, 5.18 and 5.19 contain the calculated values of $\overline{v}$ for these data.

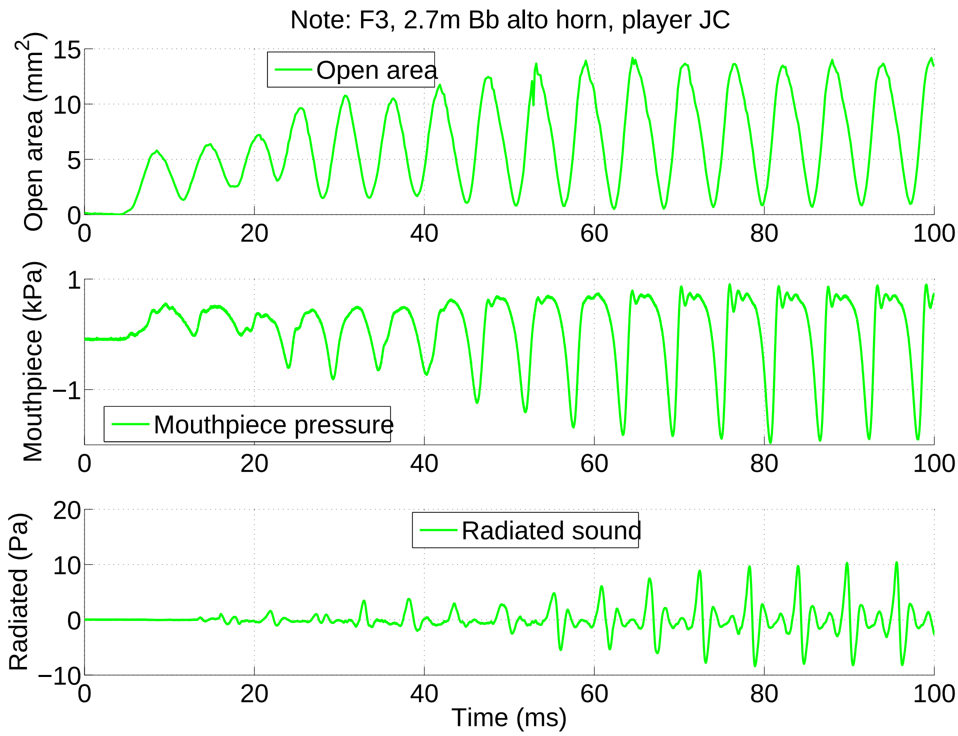


Figure 5.15: *Starting transient for the note F_3 on the 2.7 m horn in B♭-alto. The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***JC***

The behaviour of the lip frequency of player LN here is very similar to that of player HP when playing the note F_3 on the *B*♭-basso horn (see figure 5.13), with an initial frequency much higher than that of the target. The oscillation then decreases in frequency, but never drops below the target pitch of 174Hz. Again, the steady-state value of $\overline{\nu}$ for this player is several Hz higher than the target, perhaps indicating that the instrument was out of tune. However, since this behaviour has been observed twice on this player it may be that the instrument is not out of tune, but rather evidence of something else. Playing *above* the resonance frequency of the instrument is indicative of the behaviour of an outward-striking reed [Richards, 2003] so it may be that the embouchure chosen by player LN is outward-striking in nature. It would be interesting to

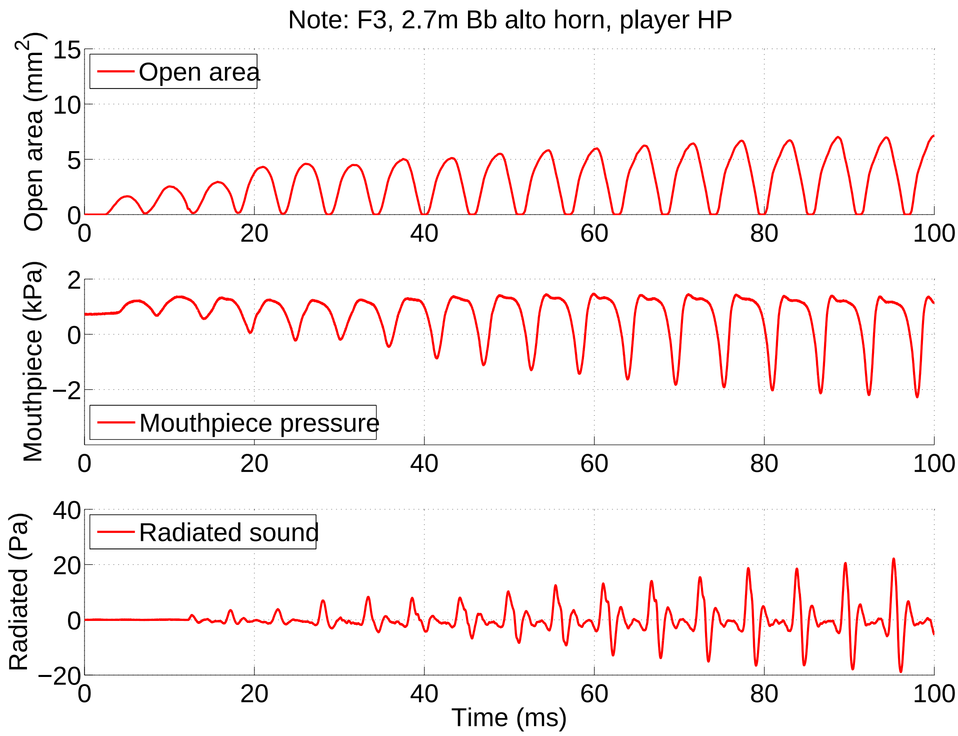


Figure 5.16: *Starting transient for the note* F_3 *on the* 2.7 *m horn in B♭-alto. The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***HP***

use the method of Newton *et al.* [2008] to determine the nature of this player's embouchure in this case.

Player JC, on the other hand, starts his lip vibration at a much lower frequency than the target. It then rapidly increases until over 30Hz above the target pitch and then decreases. As in the previous note the value of $\overline{\nu}$ seems to oscillate around the target value from cycle to cycle. Finally, the behaviour of the lips of player HP seems more similar to that of player LN than that of player JC. $\overline{\nu}$ remains well above the target frequency for the first five cycles of the motion and then becomes approximately constant during the steady state. Note that once again there are very few cycles for which the oscillation frequency is lower than the target frequency. It appears that

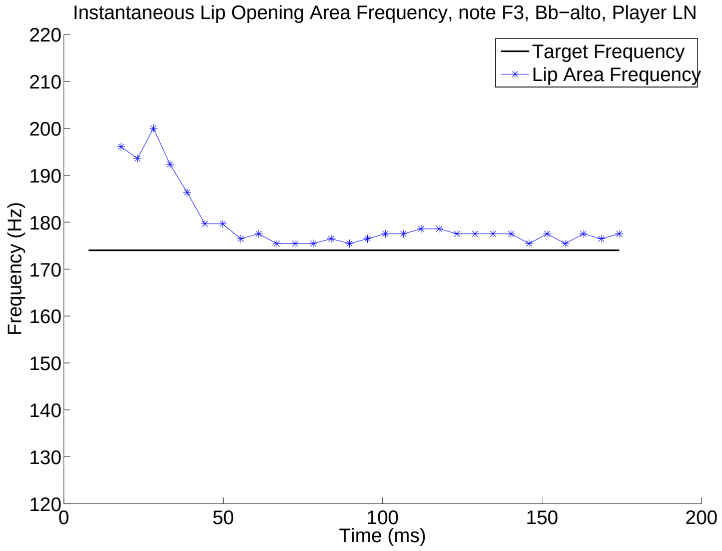


Figure 5.17: *Instantaneous lip opening area frequency ($\overline{v}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note F_3, B♭-alto horn. Player* ***LN***

player HP demonstrated the most consistent behaviour of instantaneous lip opening area frequency during performance of these two notes. In both cases, this player kept the oscillation frequency of the lips higher than the target frequency for the vast majority of the transient. This player is a very experienced professional and as such it is not unexpected that the behaviour of his lips is consistent. On the other hand, as noted previously this player was not entirely comfortable with the experimental process and so it may be that the lips of this musician would behave differently under 'normal' circumstances. However, the lips of player LN also very rarely oscillate at a frequency lower than the target frequency. In order to draw firm conclusions about the desirability of different transient behaviour it would be necessary to repeat these measurements with many different players. Questioning the musicians about what they believe they are trying to do during the transient

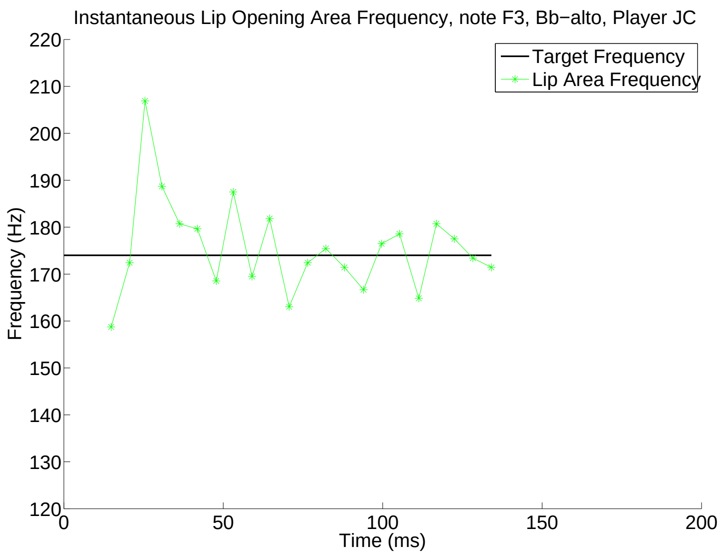


Figure 5.18: *Instantaneous lip opening area frequency ($\overline{v}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note F_3, B♭-alto horn. Player **JC***

may also aid in this respect; perhaps there are different schools of thought, practice, or training which may lead to differences between the transient behaviour of the lips.

However, even though it has been hard to make definitive conclusions about the behaviour of the lips of brass players during the starting transient, the information obtained will still be of great use as a guide when creating a physical model of the lips. There have, until now, been very few measurements of what happens to the lips during the starting transient. Now that these preliminary measurements have been completed it will be possible to compare the behaviour of computational models and see whether or not the behaviour obtained is realistic.

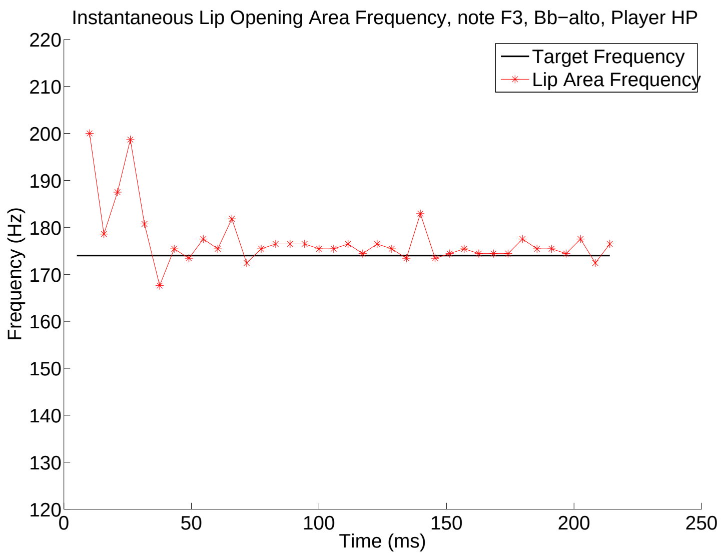


Figure 5.19: *Instantaneous lip opening area frequency ($\overline{v}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note F_3, $B\flat$-alto horn. Player* ***HP***

5.6.3 Notes F_3 and $B\flat_3$, tenor trombone

Recordings were also made on a tenor trombone, similar in length to the $B\flat$-alto horn. In this case, the player was asked to play the same pitch twice, but with the slide of the instrument in two different positions. For the note F_3 measurements were taken in first and sixth position, and for the note $B\flat_3$ in first and fifth position. Figures 5.20 to 5.23 show the transient behaviour of the note F_3 played by player TJ in first and sixth positions, whilst figures 5.24 to 5.27 show the same information but for the note $B\flat_3$ in first and fifth positions.

Consider first the note F_3. With the trombone in first position, the reinforcement of all three signals can be seen as expected after three cycles (F_3 is the third mode of the instrument in this instance). The amplitude of the lip opening area is particularly small. Examining the video footage it appears that the top lip of this player overhangs the bottom by a significant amount.

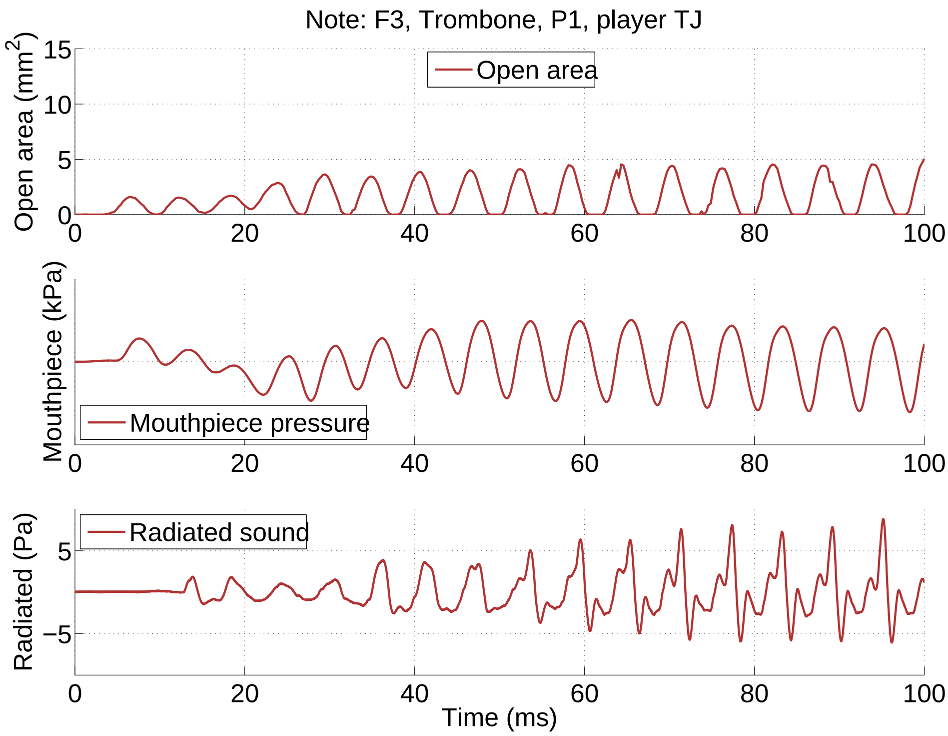


Figure 5.20: *Starting transient for the note F_3 on the tenor trombone in first position. The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***TJ***

However, there are no unusual features in the form of the mouthpiece pressure signal. In sixth position the behaviour is very similar, except for the expected delay in acoustical feedback. There is, however, a marked change in the form of the steady state radiated sounds between first and sixth positions. It appears that there may be little difference between starting transients for the two recordings but that the perceived final sound may well be different. Examining the instantaneous lip opening area for these notes (figures 5.22 and 5.23) it can be seen that there are less variations from the target frequency than in the case of the three horn musicians. The player begins the lip oscillation at a frequency very close to the target, and there is then little variation in the value of $\overline{v}$. It is interesting to note that for the majority of the recording the

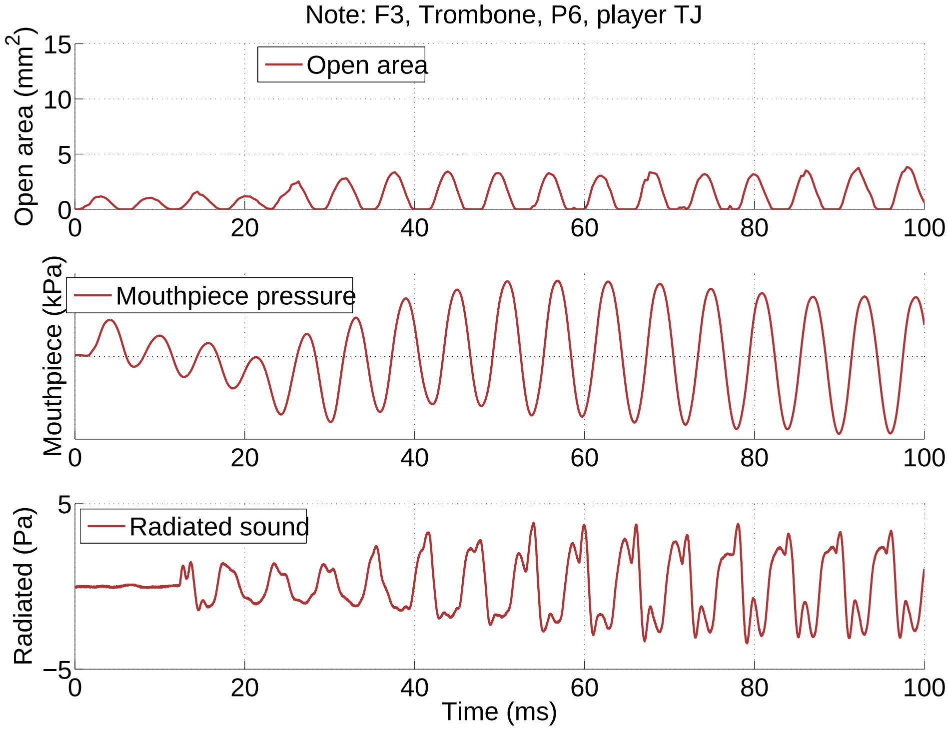


Figure 5.21: *Starting transient for the note F3 on the tenor trombone in sixth position. The lip opening area, mouthpiece pressure and radiated sound are shown. Player **TJ***

player's lip oscillation is slightly flat of the target. This is again in contrast to the behaviour of the lips of the horn musicians.

Turning now to the note *B*♭3 in first and fifth positions we see behaviour that is very consistent with the recordings of the note *F*3. However, we see here that the lip opening area is even smaller (amplitude decreases with an increase in pitch). Unfortunately extracting the open area data from these small amplitude recordings is difficult, and there are a few peaks in the opening area caused by the 'noise' inherent with measuring a small signal. These peaks have caused some large amplitude 'spikes' in the behaviour of $\overline{v}$ for these notes. Ignoring these, we see that once again the majority of lip oscillation cycles occur at a frequency below the target frequency.

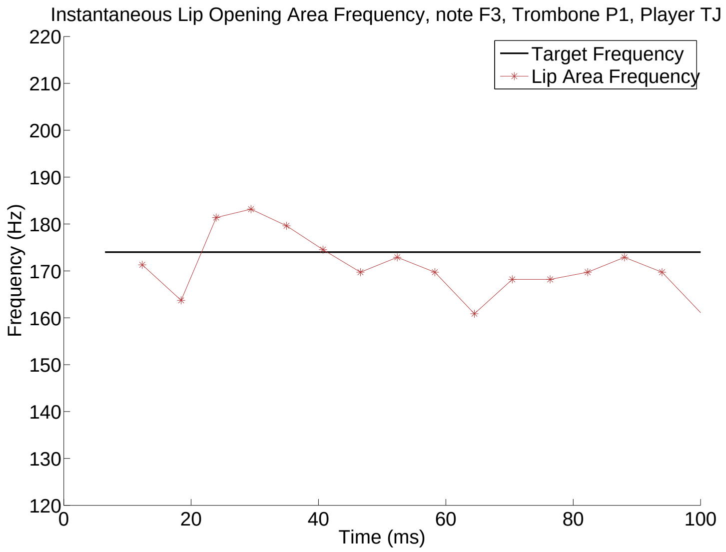


Figure 5.22: *Instantaneous lip opening area frequency ($\overline{\nu}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note F_3, tenor trombone in first position. Player* ***TJ***

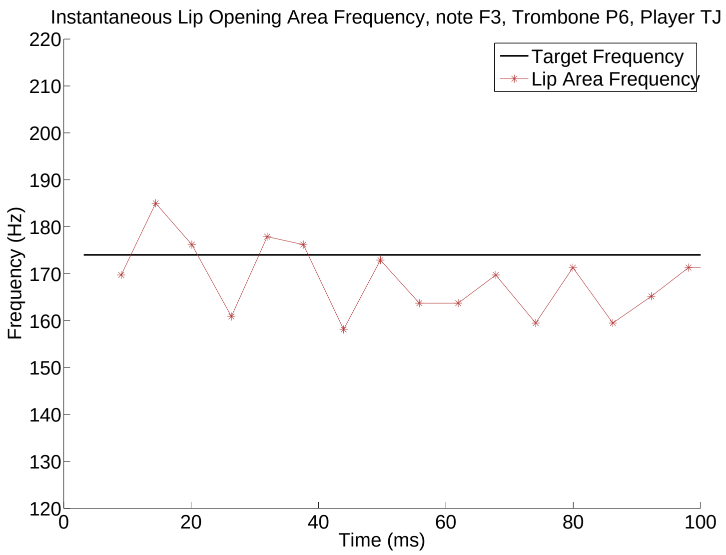


Figure 5.23: *Instantaneous lip opening area frequency ($\overline{\nu}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note F_3, tenor trombone in sixth position. Player* ***TJ***

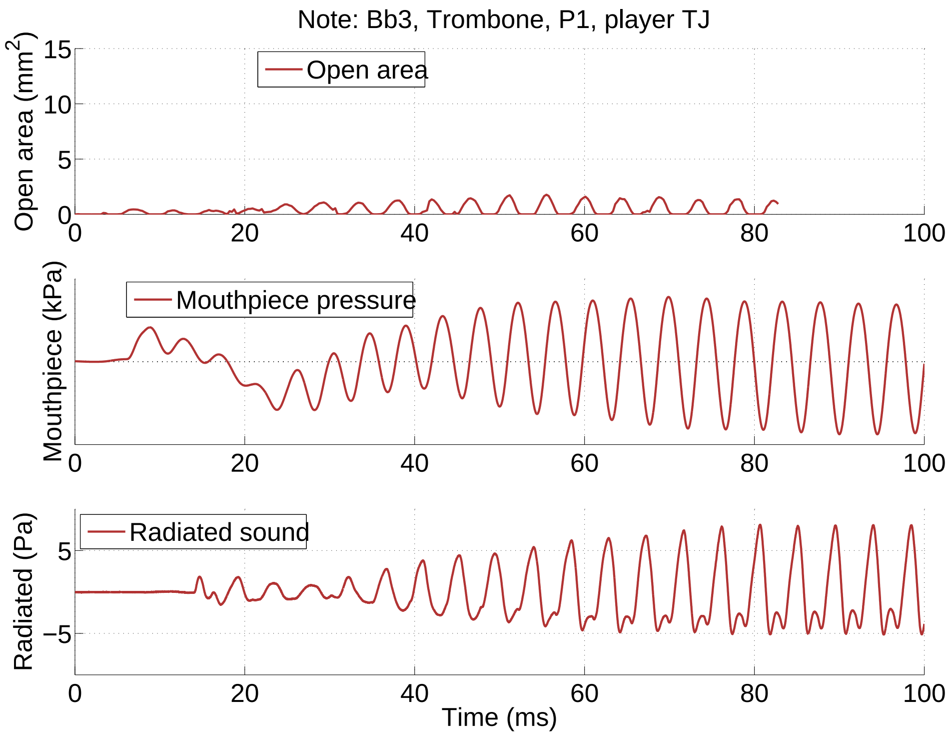


Figure 5.24: *Starting transient for the note B♭3 on the tenor trombone in first position. The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***TJ***

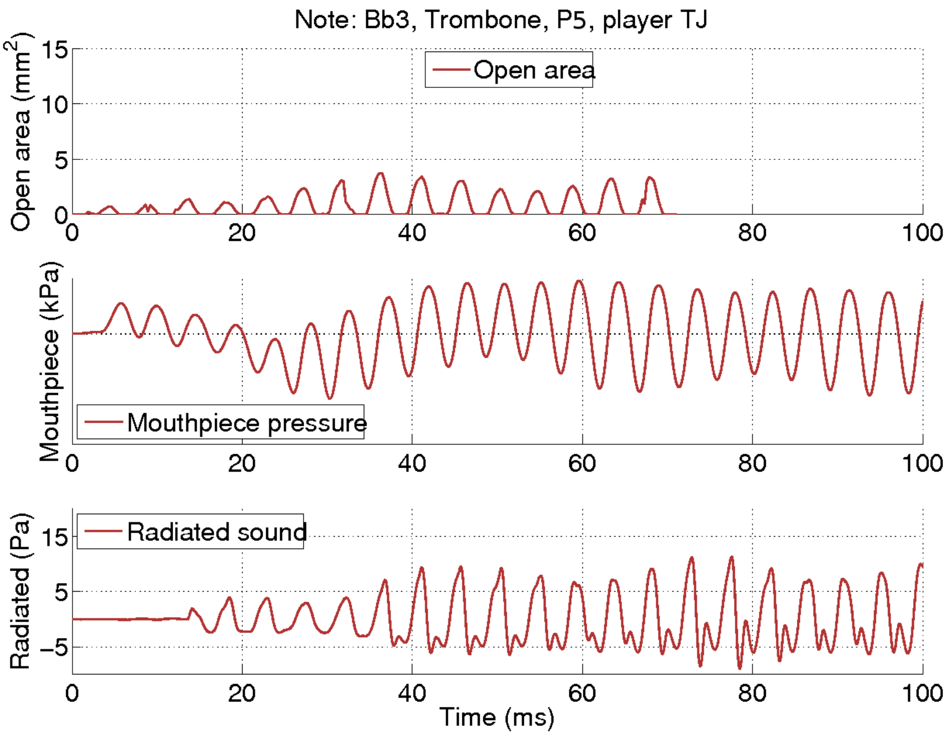


Figure 5.25: *Starting transient for the note B♭3 on the tenor trombone in fifth position. The lip opening area, mouthpiece pressure and radiated sound are shown. Player **TJ***

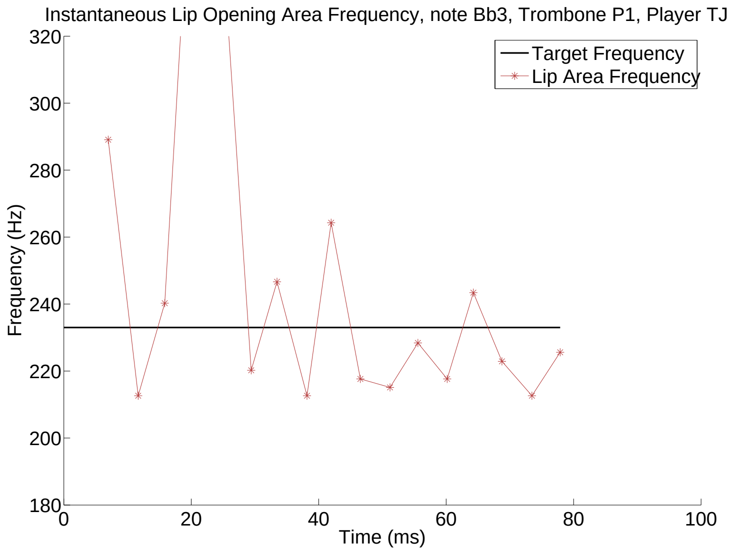


Figure 5.26: *Instantaneous lip opening area frequency ($\overline{v}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note B♭3, tenor trombone in first position. Player **TJ***

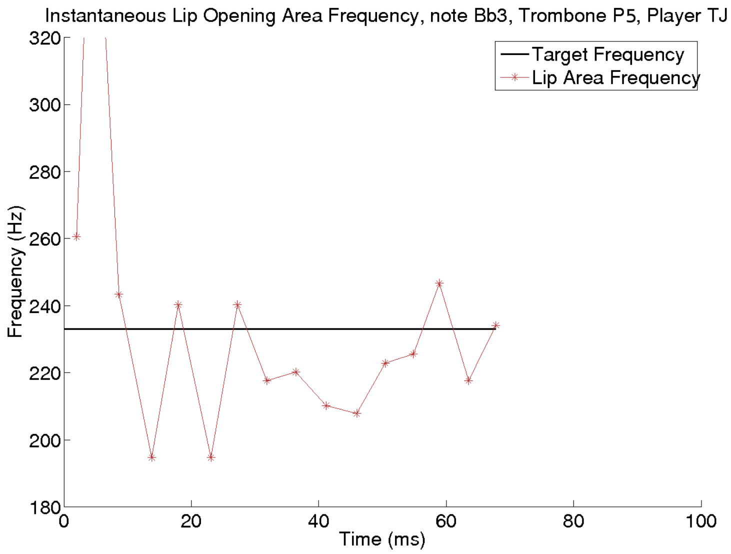


Figure 5.27: *Instantaneous lip opening area frequency ($\overline{v}$) during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note B♭3, tenor trombone in fifth position. Player **TJ***

5.6.4 Notes F_3 and $B\flat_2$, bass trombone

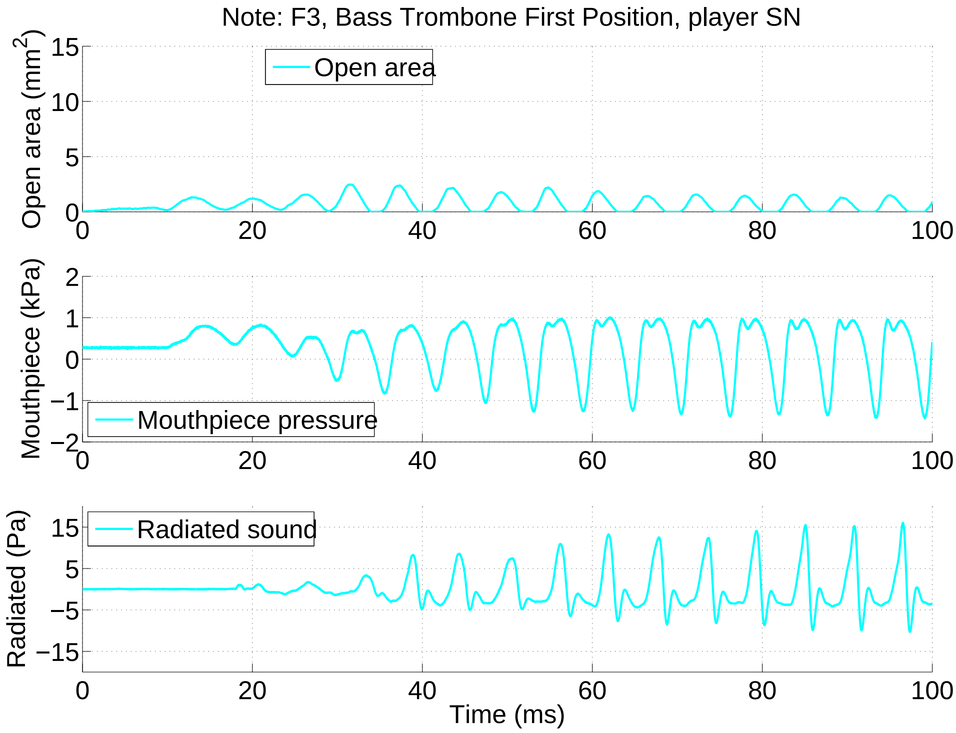


Figure 5.28: *Starting transient for the note F_3 on the bass trombone in first position. The lip opening area, mouthpiece pressure and radiated sound are shown. Player* **SN**

Recordings of the starting transient on the bass trombone were made with two different instrument lengths. The first position chosen was first position, with the slide fully retracted. The second was in the fifth position with the trigger depressed. In this configuration, the bass trombone is approximately the same length as a $B\flat$-basso horn.

Figures 5.28 and 5.29 show the transient behaviour of the note F_3 played on the bass trombone in first position as played by player SN. The top lip of this player appears to overhang the bottom lip significantly and unfortunately it was not possible to capture the open area data for this player with the

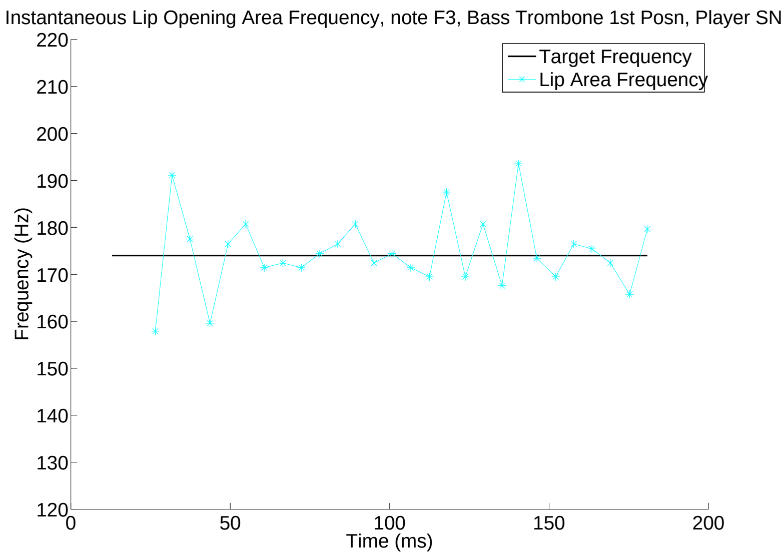


Figure 5.29: *Instantaneous lip opening area frequency during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note F_3, bass trombone in first position. Player* ***SN***

trombone in the 'basso' position. Examination of the instantaneous open area frequency for this player suggests that the first few cycles oscillate around the target before becoming more constant in frequency as the acoustic feedback reinforces the oscillation.

Typical recordings of the note $B\flat_2$ in both first and 'basso' positions on the bass trombone by player MF can be seen in figures 5.30 to 5.33. The transient behaviour of the lips of this player is very similar to those that we have seen already. For the shorter instrument the time taken for acoustical feedback to reach the mouthpiece is shorter than in the case of the longer instrument, as expected. Looking at the instantaneous lip opening area frequencies in figures 5.32 and 5.33 we see that in both notes the musician has begun lip oscillation slightly below the target frequency. This is in contrast to the three horn players who consistently began their notes *above* the frequency of the intended pitch.

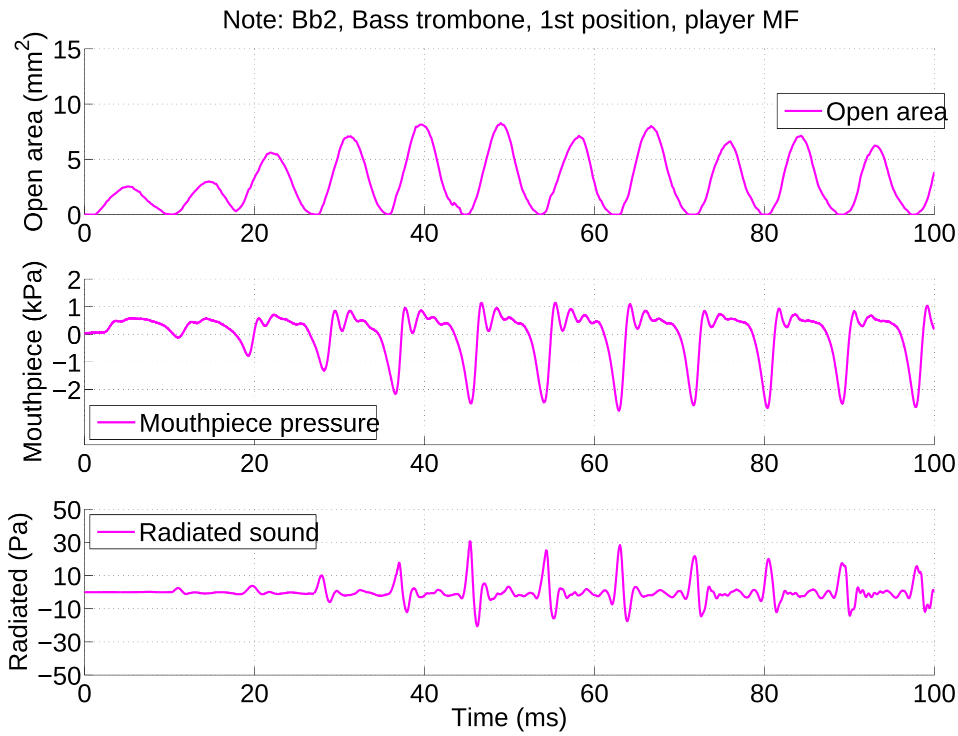


Figure 5.30: *Starting transient for the note B$\flat_2$ on the bass trombone in first position. The lip opening area, mouthpiece pressure and radiated sound are shown. Player **MF***

The measurements reported here show that, for the limited number of cases studied, the transients on brass instruments are considerably influenced by the delay between the start of lip vibration and the return of the first reflection to the mouthpiece. Benade [1969] has suggested that a significant difference between the group velocity and phase velocity for a particular note played on a specific instrument could explain difficulties in starting the note. More extensive studies are required to establish how consistent the behaviour of the starting transient is across repetitions of the same note by a particular player, and to what extent the 'playability' of an instrument can be identified with specific features of its reflection coefficient.

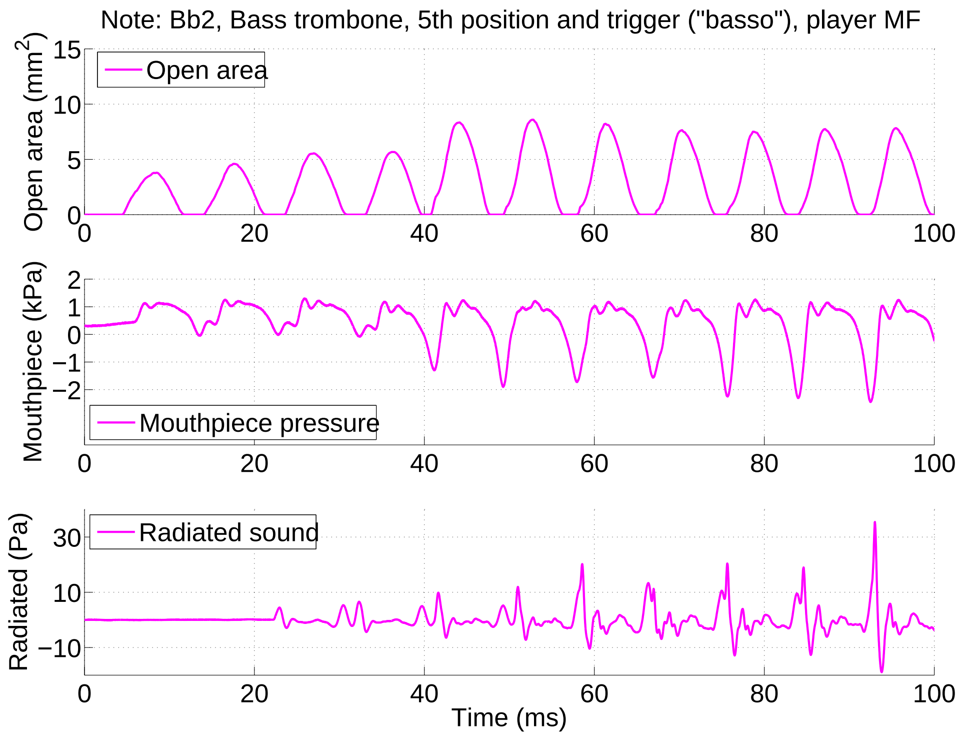


Figure 5.31: *Starting transient for the note B♭$_2$ on the bass trombone in fifth position plus trigger (effectively a B♭-basso trombone). The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***MF***

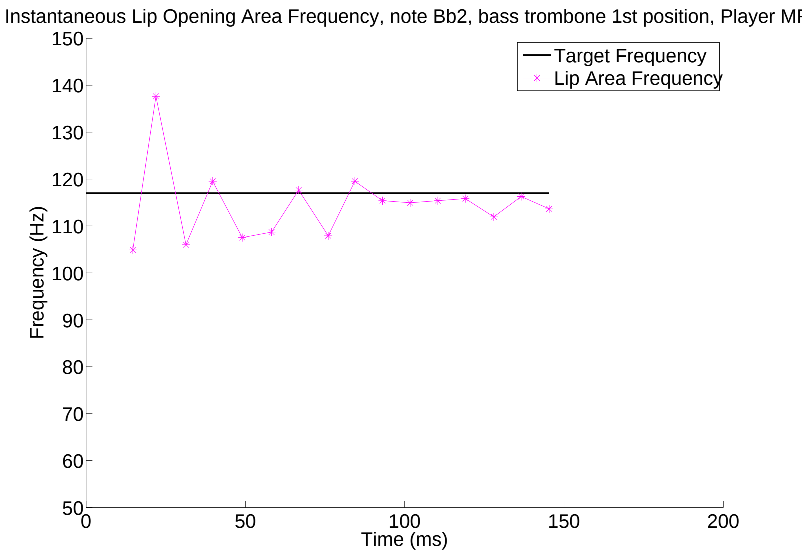


Figure 5.32: *Instantaneous lip opening area frequency during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note $B\flat_2$, bass trombone in first position. Player* ***MF***

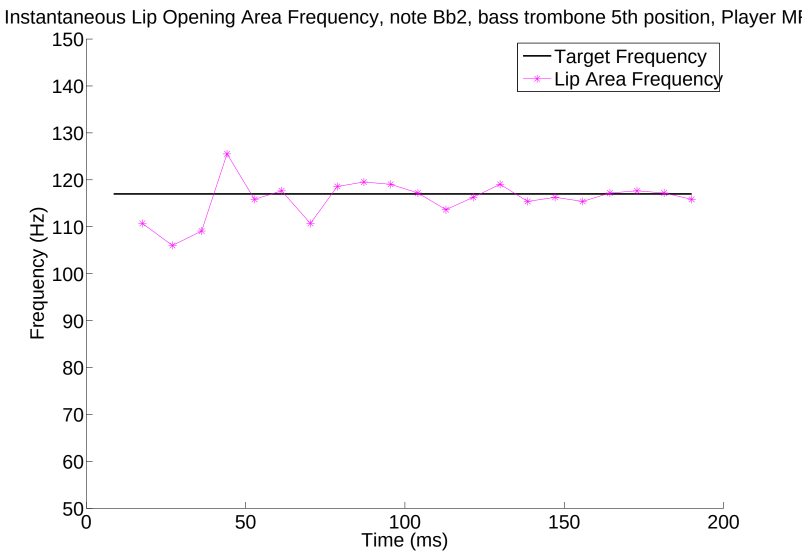


Figure 5.33: *Instantaneous lip opening area frequency during the starting transient. The target frequency is the frequency of the target note, with $A = 440Hz$. Note $B\flat_2$, bass trombone in fifth position plus trigger. Player* ***MF***

5.7 Slurs

One extremely common feature of brass wind instrument playing is the ‘slur’, where a player changes smoothly from one pitch to another. The musician achieves this by a combination of a change in embouchure, typically altering the lip tension, air-flow, and mouthpiece pressure. If the note to which they are changing is not one of the resonant modes of the instrument then they will also need to change the length of the instrument with the use of either slide or valves. If the destination note *is* one of the resonant modes of the instrument then they can achieve the slur entirely through a change in embouchure and mouthpiece pressure. Musicians typically refer to this technique as a *lip-slur*. Players believe that they are able to achieve a different sounding slur by altering the manner in which they alter their embouchure whilst changing notes [Farkas, 1956] and spend many hours practicing to achieve the desired effect [Norman, 2009].

5.7.1 Slur measurements: method

There have been several studies of variation in impedance of valved instruments during slurring [Widholm, 1997; Widholm, 2005]. In this work the experimental procedure and analysis method detailed in section 5.3 were used to measure the lip opening area, mouthpiece pressure, and radiated sound for two different horn players during two different lip-slurs. The first was a slur from D_3 to D_4 (an octave) between the fourth and eighth modes of the horn in open D. The second was between the third and fourth modes of the horn in F, corresponding to an interval of a perfect fourth between the notes C_3 and F_3. Both slurs were performed by both musicians on the same instrument, an early 20th century narrow bore horn by Boosey and Hawkes.

These two players were chosen because they practice different techniques for lip-slurring. The first player, LN, follows the teachings of Farkas [1956] and describes their style of lip-slur as follows:

> 'my main aim is to keep the note going during the slur by supporting the note with more air as the note moves from one to the next (upwards). In doing so, it feels to me as if I am very briefly 'catching' some of the intermediate resonances on the way up. In a way, I use the feeling of the notes during the slur, to predict when I'm about to hit the upper note, so that I don't split it, but it all happens very quickly! I prefer to do that then reduce the air pressure in between which I know a lot of players do, as then it feels a bit more like a blind jump'

The second player, JC, uses a different style of lip-slur which they describe as:

> 'I...aim to get from one note to another with the least hiatus in the sound along the way. Years of practice have lead me to believe that this could be achieved by blowing continuously through the slur, which consisted of a very rapid repositioning/tensioning of the embouchure coupled with a strong conviction of 'where the next note *is*.' '

5.7.2 Lip-slurs: results

Figure 5.34 shows the lip opening area, mouthpiece pressure, and radiated sound for the slur D_3 to D_4 performed by player LN. It can be seen clearly that the transition begins around 40ms, where the lip opening area begins

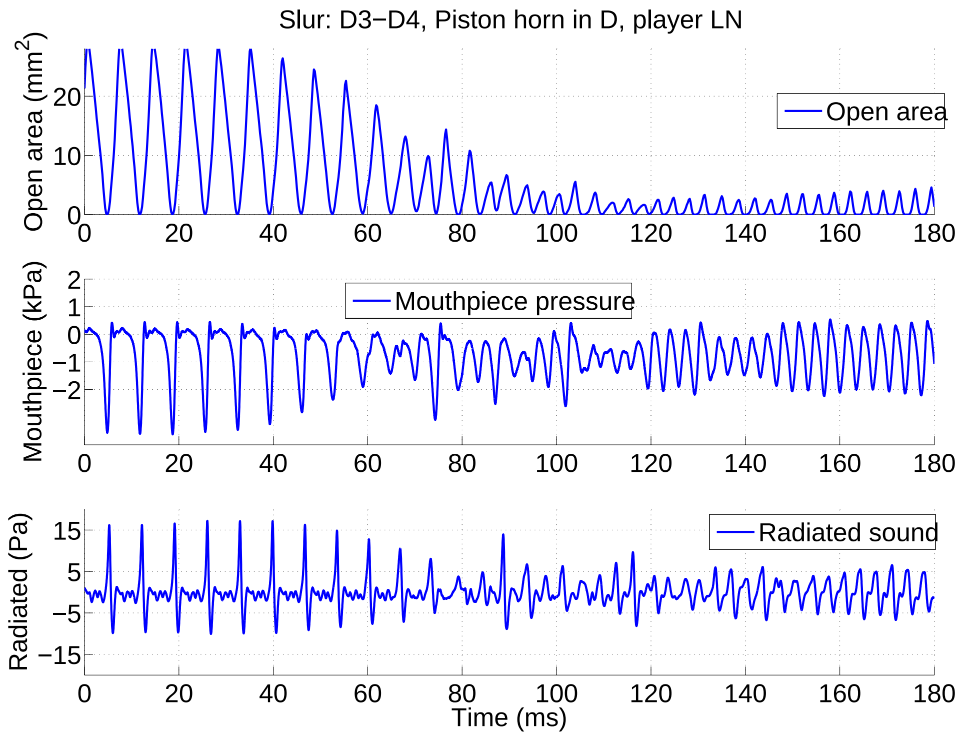


Figure 5.34: *Transient for the slur D_3 to D_4 on piston horn in D (fourth mode to eighth mode). The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***LN***

to steadily decrease. The area continues to decrease throughout the slur and when the steady state of the second note is achieved (around 150ms) the amplitude of the lip opening area is considerably smaller than it was for the first note. The lips appear to continue to oscillate through the entire process. Examining the mouthpiece pressure during the slur, we see that the form of the pressure signal varies greatly. The radiated sound shows similar behaviour. Figure 5.35 shows the calculated values of $\overline{\nu}$ during this slur. The lip oscillation remains at a steady frequency until approximately 60ms (20ms *after* the lip opening area begins to decrease). Then, it appears to 'sweep' through a succession of higher frequencies, overshooting the destination frequency

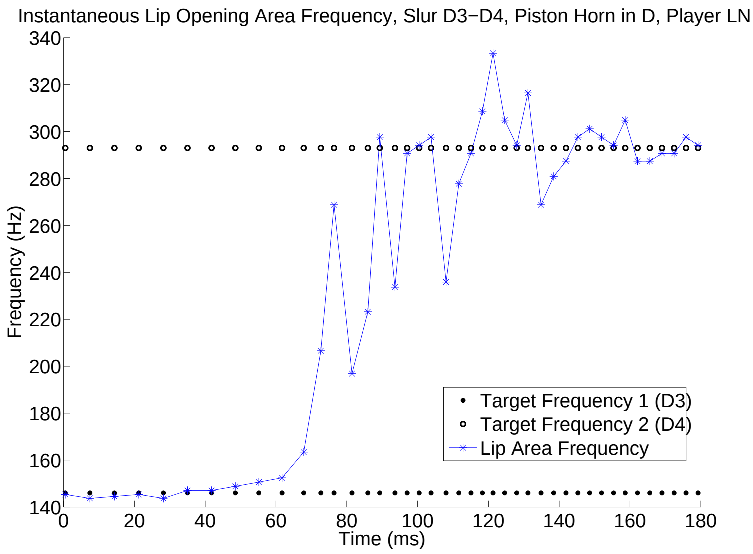


Figure 5.35: *Instantaneous lip opening area frequency $\overline{\nu}$ during the slur D_3 to D_4 (fourth mode to eighth mode) on horn in D. The target frequency is the frequency of the played notes, with $A = 440$Hz. Player* ***LN***

before settling back down to the frequency of the second note when the steady state is achieved. The intermediate values of $\overline{\nu}$ do not appear to correspond to any resonances of the instrument. The whole lip-slur appears to take around 100ms (steady state to steady state), which is around twice the time for a typical starting transient.

Turning now to figures 5.36 and 5.37 we can examine a typical slur from D_3 to D_4 by player JC. As in the case of player LN, we again see the lip opening area decrease in amplitude as the player approaches the change of pitch. Around 50ms the lip opening area stays approximately constant for between 5 and 10ms, suggesting that the lips are no longer oscillating at this point. The oscillation then begins again with one very large amplitude oscillation. Around 120ms we have reached the steady state regime of the second note. Perusal of the mouthpiece pressure over this period shows that

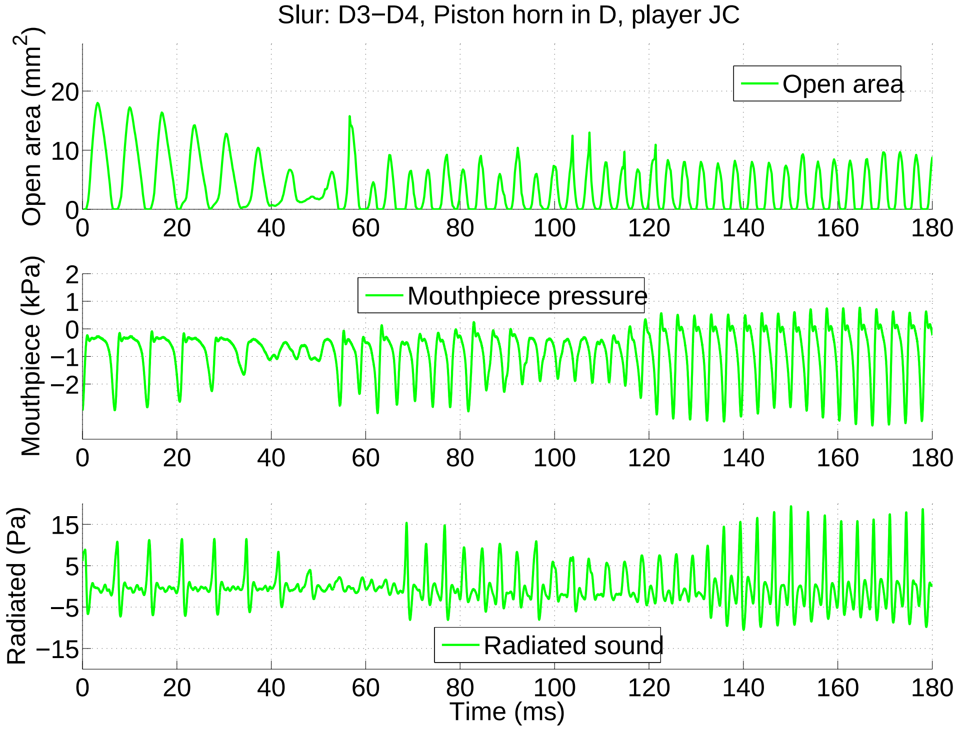


Figure 5.36: *Transient for the slur D_3 to D_4 (fourth mode to eighth mode) on horn in D. The lip opening area, mouthpiece pressure and radiated sound are shown. Player **JC***

the form of the pressure signal is much simpler than in the previous case with player LN. Examining the radiated sound between 40 and 70ms it appears that the radiated sound has essentially disappeared. Indeed, on listening to the radiated sound slowed down by factor two it is possible to hear a distinct 'break' in the sound. It appears that in this case the player has not achieved a smooth slur but has in fact stopped playing for a very brief instant before very quickly beginning the second note. Again, the time period for the whole lip-slur is around twice that of a typical starting transient. It is interesting to note, however, that even though this player appears to have treated this slur as two separate notes played in quick succession the instantaneous lip opening

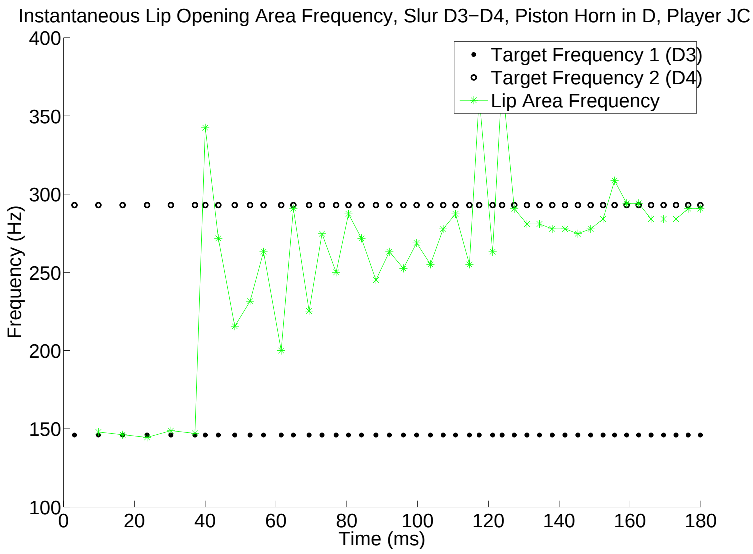


Figure 5.37: *Instantaneous lip opening area frequency $\overline{\nu}$ during the slur D_3 to D_4 (fourth mode to eighth mode) on horn in D. The target frequency is the frequency of the played notes, with $A = 440$Hz. Player **JC***

area, $\overline{\nu}$, behaves differently here in comparison to that measured during a 'normal' starting transient by the same player (for example, figure 5.12). It should also be noted that the player has stated that the experimental setup—with unorthodox mouthpiece and unusual position of the instrument—made it harder to perform a slur to his usual level. It may well be that the current setup is slightly too awkward for the study of the finer details of instrumental technique.

Figures 5.38 to 5.41 show typical slurs from C_3 to F_3—third mode to fourth mode, on the horn in F—as played by players LN and JC. It can be seen clearly that the manner in which both players approached the slur is similar to the octave slurs presented in figures 5.34 to 5.37. For player LN, there are no obvious discontinuities in the motion of the lips, the mouthpiece pressure, or the radiated sound. In this case, the player seems to have moved smoothly

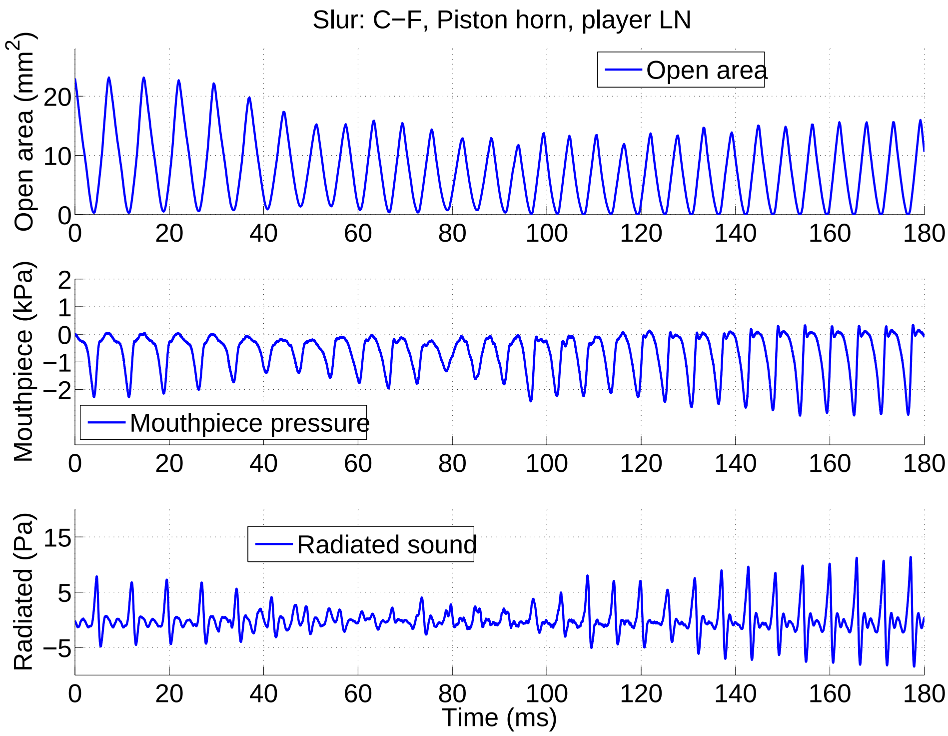


Figure 5.38: *Transient for the slur C_3 to F_3 (third mode to fourth mode) on the horn in F. The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***LN***

from one note to the next without any hiatus. The behaviour of $\overline{v}$ for this recording shows that, once again, the player has reached the target frequency via a series of intermediate steps. This is consistent with both the stated intentions of the musician and with the slur behaviour seen previously. For player JC, there are no clear discontinuities in the data presented in figure 5.40. This is in contrast to the manner in which this musician performed the slur D_3 to D_4 where there was a definite 'break' in the sound. In the case of the slur C_3 to F_3 the musician is changing between consecutive modes, whereas in the octave slur they were moving between the fourth and eighth modes. It may be that for a small change in mode number it is simple for this musician to

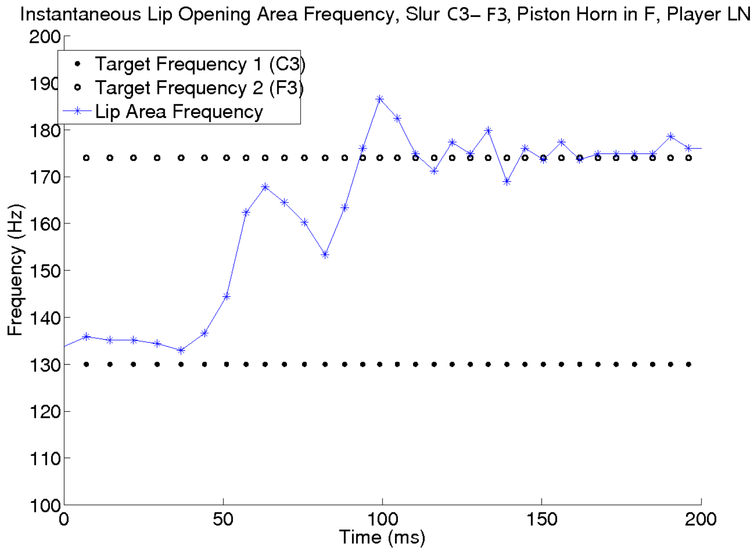


Figure 5.39: *Instantaneous lip opening area frequency $\overline{v}$ during the slur C_3 to F_3 (third mode to fourth mode) on horn in F. The target frequency is the frequency of the played notes, with $A = 440$Hz. Player* ***LN***

'predict' where the next mode lies and modify their embouchure accordingly whilst for a larger change it is simpler (or more accurate) to quickly stop the oscillation and then form a new note.

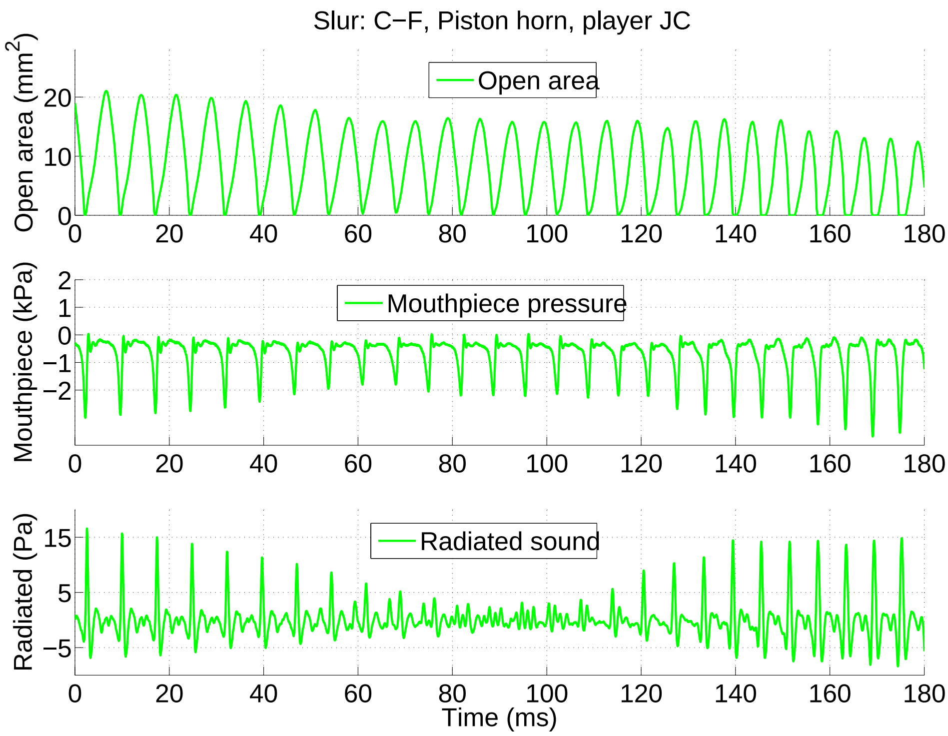


Figure 5.40: *Transient for the slur C_3 to F_3 (third mode to fourth mode) on the horn in F. The lip opening area, mouthpiece pressure and radiated sound are shown. Player* ***JC***

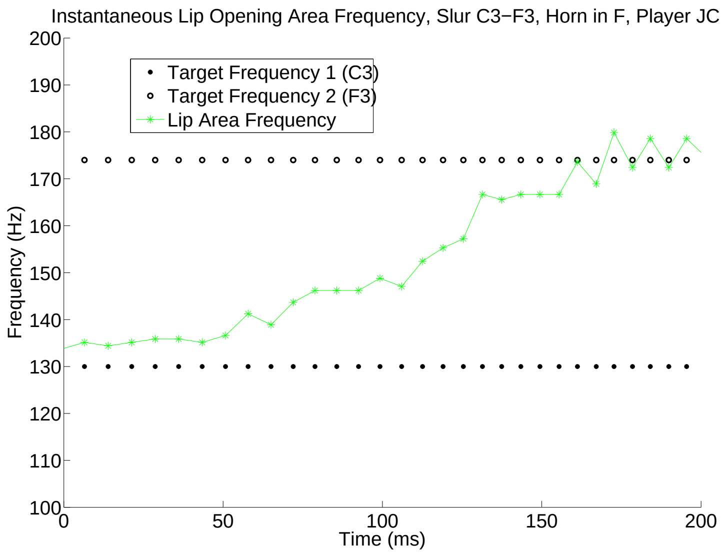


Figure 5.41: *Instantaneous lip opening area frequency $\overline{v}$ during the slur C_3 to F_3 (third mode to fourth mode) on horn in F. The target frequency is the frequency of the played notes, with $A = 440$Hz. Player* ***JC***

5.8 Transient behaviour: conclusions

Lip opening areas, mouthpiece pressures and radiated sounds were measured for a variety of different musicians on a number of different instruments. All the data reinforce the theory of an initial pulse travelling the length of the instrument before being reflected at the bell. Once the pulse returns to the mouthpiece the oscillation is reinforced. The time to reach the steady state regime was, in all cases, no longer than 50ms. However, the behaviour of the lips and mouthpiece pressure is not consistent from player to player. It would be immensely helpful to take a large number of repeat measurements across a large number of musicians.

Measurements of lip-slurs on the horn showed that typical time for the transition from one note to the next was of the order of twice that for a typical starting transient. Different players appear to approach the same slur in varying ways depending on their own personal technique. Repeat measurements with more musicians would be of great interest.

There are several possibilities to expand the range of measurements during the starting transient. Acoustic Pulse Reflectometry makes use of multiple microphones to separate the forward and backward-going waves as they traverse an instrument. A similar technique could be used here to study the propagation of the starting transient at various stages in the instrument. It would also be particularly interesting to study precisely what happens when a musician pushes a valve or moves the slide in conjunction with altering the embouchure. Some kind of sensor could be used to track the motion of the valve during the transient. These recommendations for further work are discussed in greater detail in section 7.3.

Chapter 6

Starting transient of the artificial mouth

'The factory of the future will have only two employees, a man and a dog. The man will be there to feed the dog. The dog will be there to keep the man from touching the equipment'

—WARREN G. BENNIS

6.1 Pressure in the mouth of the player during the starting transient

Many researchers have made use of artificial mouths to study the behaviour of brass wind instruments [Gilbert *et al.*, 1998; Cullen, 2000; Bromage, 2007]. Using an artificial mouth makes it possible to make measurements that may not be possible with a real musician, and also allows the experimentalist to fully control what the 'musician' does. Human players may make subconscious alterations to their embouchures but an artificial mouth cannot.

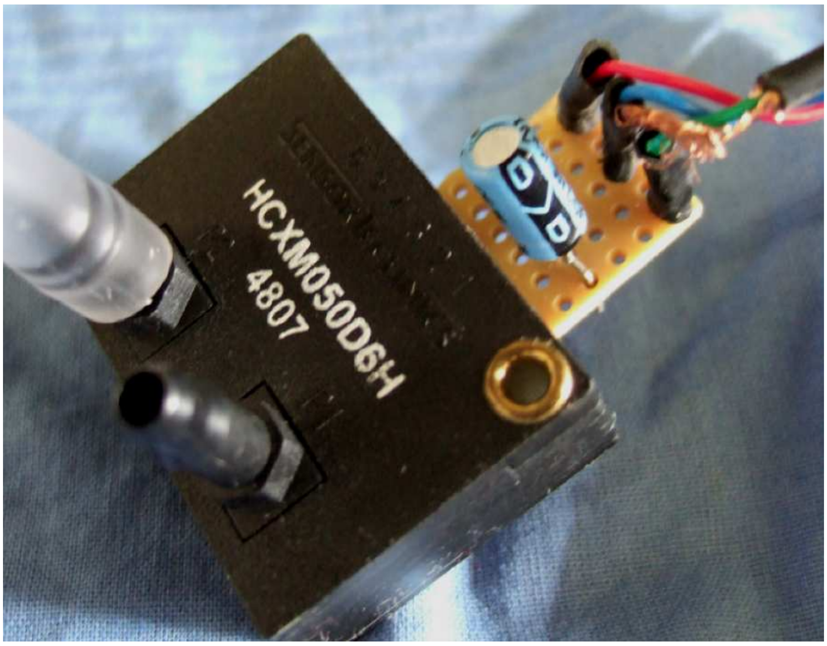


Figure 6.1: *The Sensortechnics HCXM050D6H amplified pressure sensor used to measure the pressure in the mouth during the starting transient*

Previous studies using an artificial mouth have focused on steady-state behaviour. In order to create realistic transients using the artificial mouth it is first necessary to understand what happens in the mouth of a real player as a note begins. To this end, an experiment was designed to measure the pressure in the mouth of human players during the starting transient, and to see whether the existing artificial mouth could be used to recreate this behaviour.

During an investigation of the starting transient of mechanical action organs, Woolley [2006] used a Sensortechnics amplified pressure sensor [Sensortechnics, 2009] to study the pressure build up inside the pallet of an organ during the starting transient. These sensors have a very fast response time and are also rated to work in humid conditions, making them ideal for measuring the pressure inside the mouth of a human during playing. The Sensortechnics

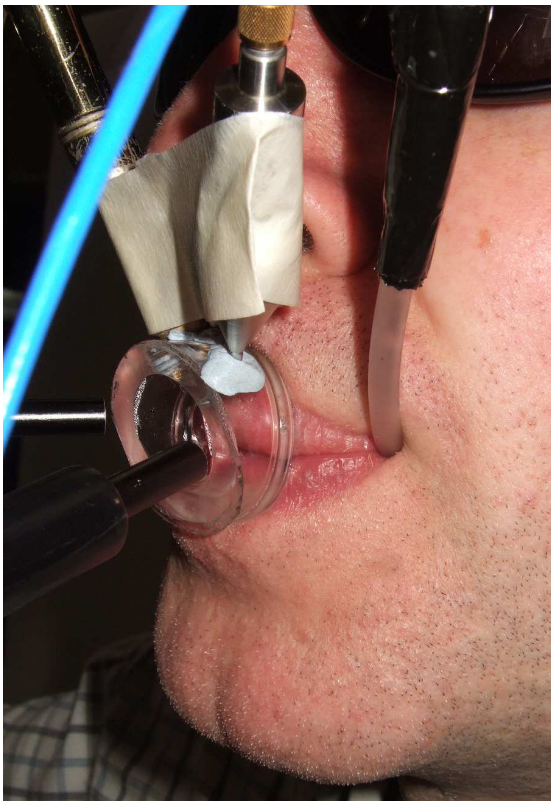


Figure 6.2: *The pressure sensor inserted into the mouth of the player. After a few minutes practice the players were able to play normally*

HCXM050D6H amplified pressure sensor is rated up to 50 mBar. Typical mouthpiece pressures during normal playing are of the order 30 mBar and so this sensor was ideal for purpose. The sensor can be seen in figure 6.1. It was important that the pressure sensor did not interfere with or distract the musician from playing as normally as possible. After discussions with several brass players, it was decided that it would be feasible to insert a small piece of plastic tubing into the side of the mouth whilst the musician was playing. The other end of the tubing was connected to the Sensortechnics HCXM050D6H, and in this way the pressure in the mouth during the starting transient could be measured. Figure 6.2 shows the piece of tubing inserted into the mouth of a player. The musicians reported that after a few minutes practice they were able to play almost entirely normally with the tubing inserted.

The output from the HCXM050D6H was recorded using PULSE along with the pressure inside the mouthpiece and the sound radiated from the bell of the instrument as before. The synchronisation process in section 5.4.1 was modified to include the signal from the Sensortechnics pressure sensor. The modified synchronisation process can be seen in figure 6.3.

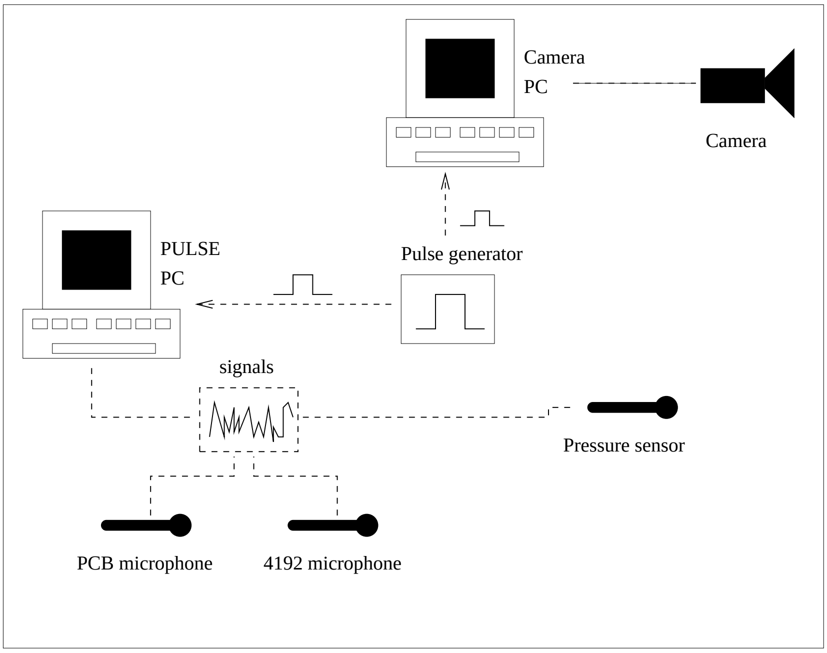


Figure 6.3: *The synchronisation process for transient measurements (see section 5.4.1) was modified slightly to include the Sensortechnics HCXM050D6H amplified pressure sensor*

6.2 Starting transients: pressure in the mouth of human players

6.2.1 Tenor trombone

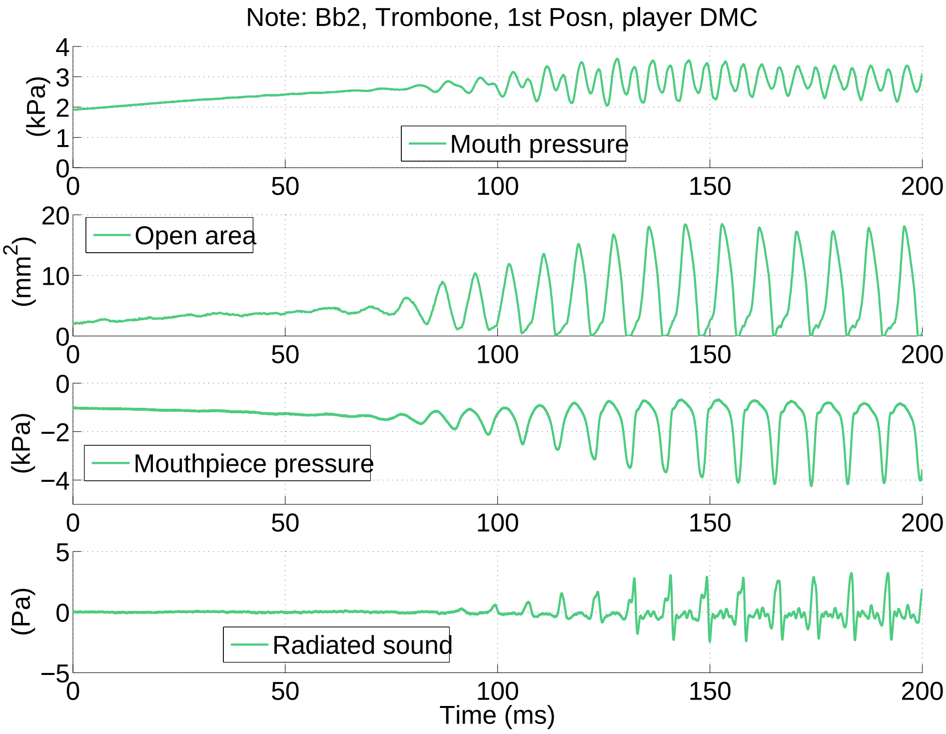


Figure 6.4: *Starting transient for the note B♭₂ on the tenor trombone in first position. The mouth pressure, lip opening area, mouthpiece pressure, and radiated sound are shown. Player* ***DMC***

Since the artificial mouth does not have any kind of tongue mechanism, the human players were asked not to articulate the notes they played for these measurements using their tongues. Figures 6.4 and 6.5 show measurements of the starting transient of the notes $B\flat_2$ and F_3 on the tenor trombone in first position played by player DMC, whilst figure 6.6 shows a recording of the note F_3 played on the same instrument by the same player, but in the sixth position.

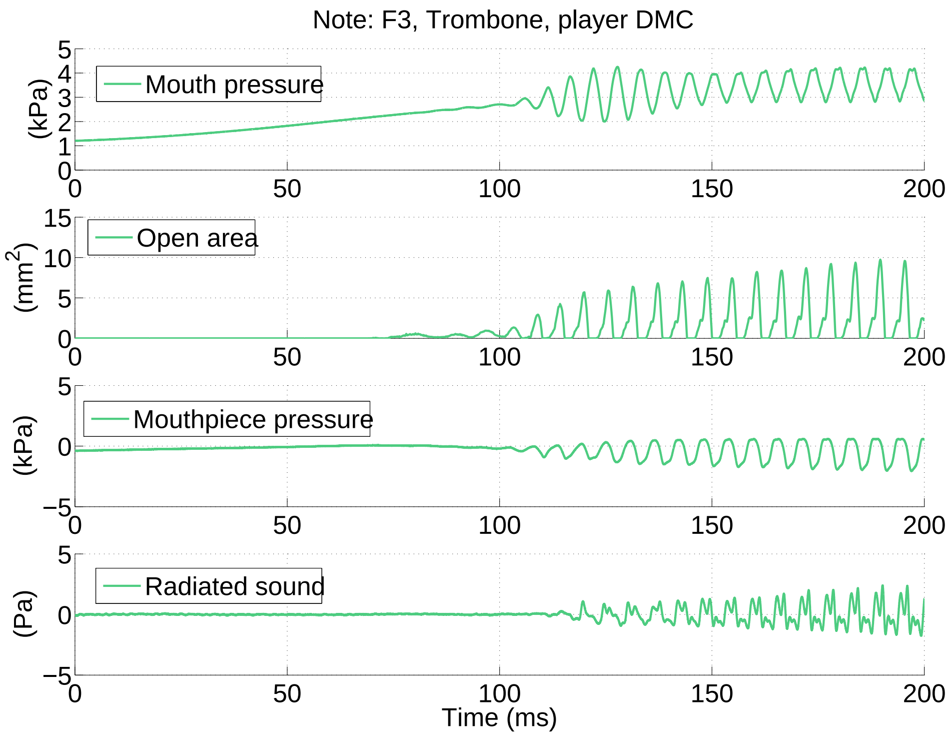


Figure 6.5: *Starting transient for the note F_3 on the tenor trombone in first position. The mouth pressure, lip opening area, mouthpiece pressure, and radiated sound are shown. Player* ***DMC***

Encouragingly, the form of the lip opening area, mouthpiece pressure, and radiated sound are consistent with the results that have been presented already. This suggests that the insertion of the pressure sensor into the mouth of the player has not negatively affected the musician whilst playing.

It should be noted that the Sensortechnics pressure sensor measures not just the acoustic pressure but the absolute pressure inside the mouth of the player. For all three notes on the trombone played by player DMC, the absolute pressure in the mouthpiece rises steadily until approximately 2.5kPa at which point the acoustic part of the oscillation begins. For the note $B\flat_2$ the pressure rise is at a rate of 10Pa/s. For the notes F_3 the pressure rise is 18Pa/s for first

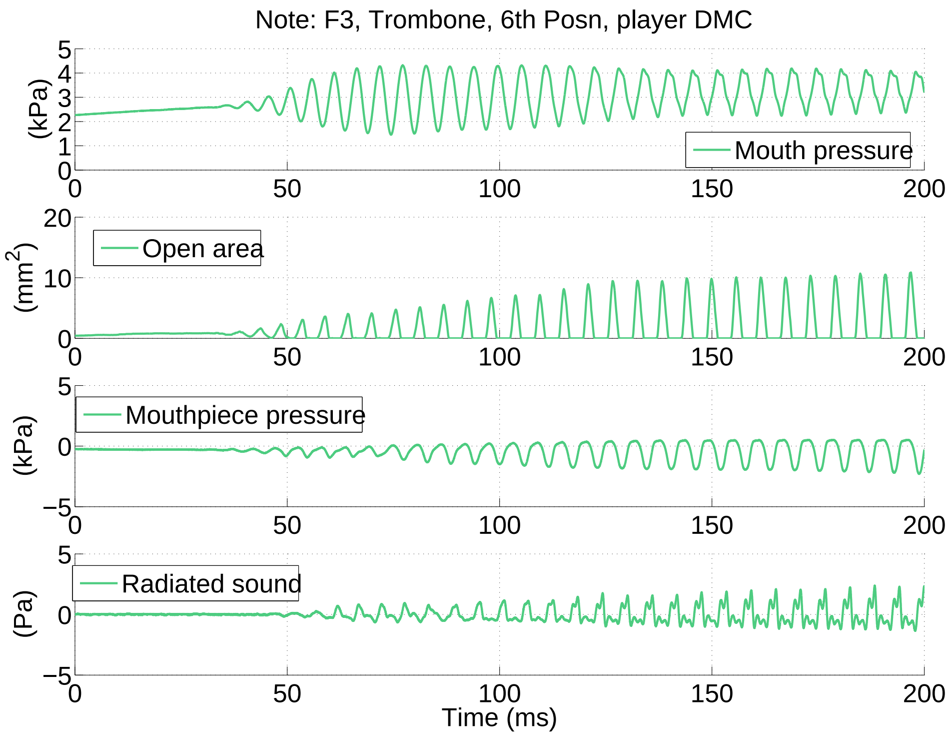


Figure 6.6: *Starting transient for the note F3 on the tenor trombone in sixth position. The mouth pressure, lip opening area, mouthpiece pressure, and radiated sound are shown. Player* ***DMC***

position and 10Pa/s for the sixth position.

In all three cases the acoustic part has approximately the same amplitude, of order 1kPa. During the note the DC component of the mouth pressure remains approximately constant. It can also be seen that, as expected, the pressure in the mouth of the player is π radians out of phase with the pressure in the mouthpiece of the instrument. That is, each maximum in mouth pressure corresponds to a minimum in the mouthpiece signal. Interestingly, the maximum amplitude of the acoustic part of the signal is found not during the steady state oscillation. The amplitude increases as the acoustic feedback from the instrument is received before lowering and 'levelling off' during the steady state part of the note.

6.2.2 Horn

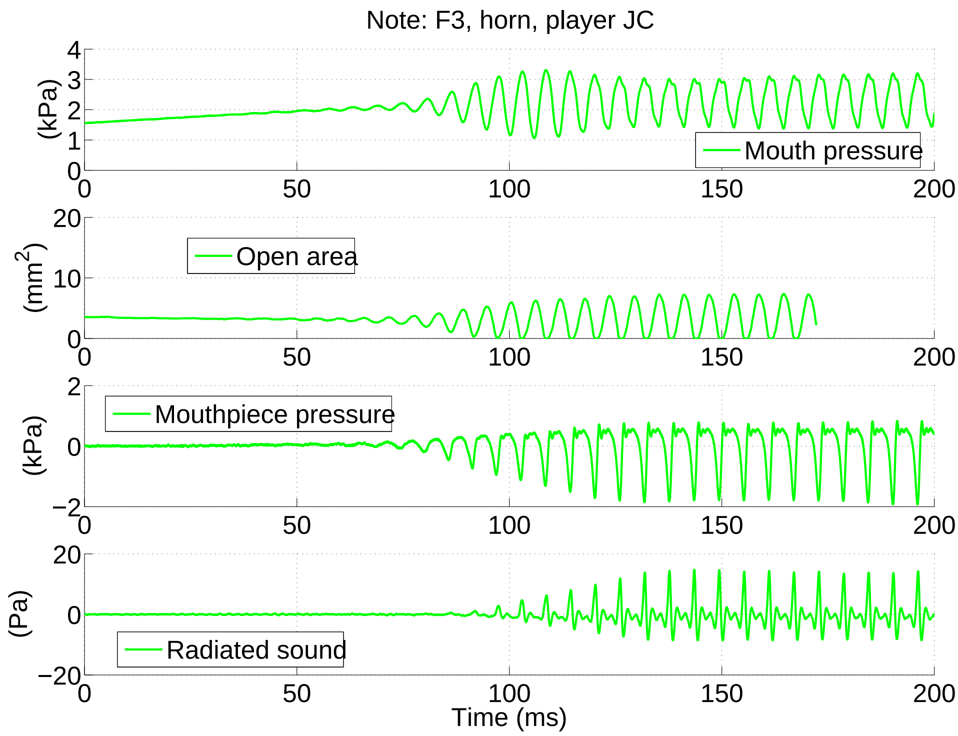


Figure 6.7: *Starting transient for the note F_3 on the horn. The mouth pressure, lip opening area, mouthpiece pressure, and radiated sound are shown. Player **JC***

Figures 6.7 and 6.8 show recordings of the note F_3 as played on horn by player JC. The first set of data shows a recording made with no valves depressed whilst the second was made with valves 2 and 3 operated, lengthening the instrument.

Again, we see that the inclusion of the pressure sensor into the mouth has not greatly altered the form of the open area, mouthpiece pressure, or radiated sound signals. The pressure in the mouth of player JC seems to be

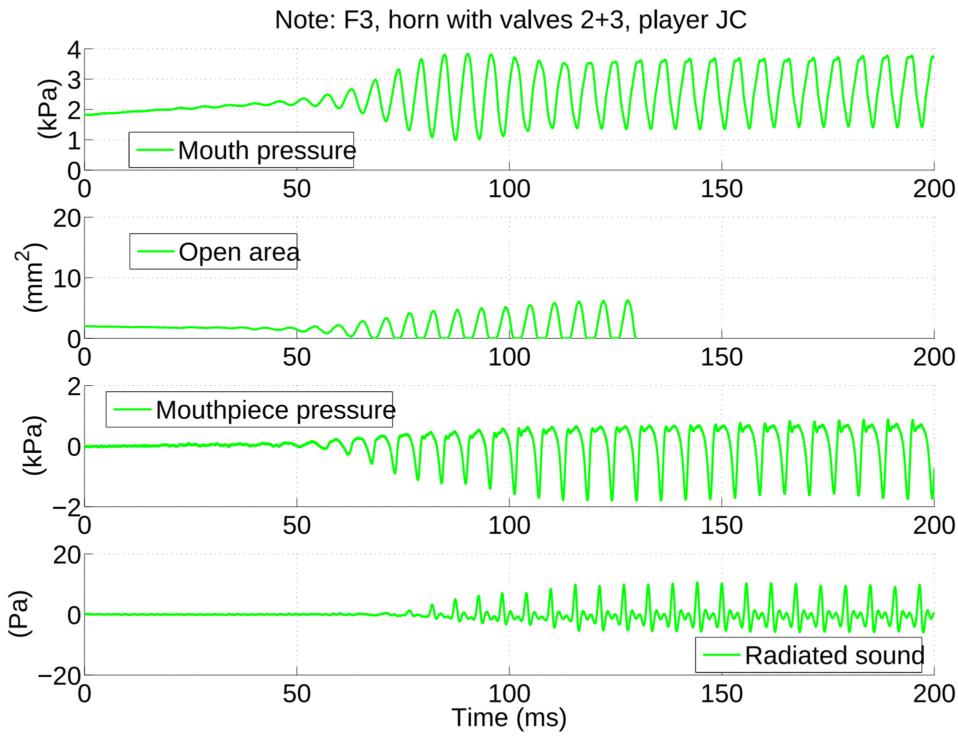


Figure 6.8: *Starting transient for the note* F_3 *on the horn with valves* 2 *and* 3 *pressed. The mouth pressure, lip opening area, mouthpiece pressure, and radiated sound are shown. Player* ***JC***

consistent with that of player DMC during the starting transient. At first, the mouthpiece pressure increases steadily until approximately 2kPa when the acoustic oscillation begins. In both measurements on the horn the pressure rise is approximately the same: 10Pa/s. This is an identical rise time to that of the notes recorded on the trombone.

In further agreement with the trombone recordings the mouth and mouthpiece pressures are once more π radians out of phase, and the amplitude of the acoustic part of the mouth pressure increases during the starting transient before decreasing and levelling during the steady state.

6.2.3 The starting transient of the artificial mouth

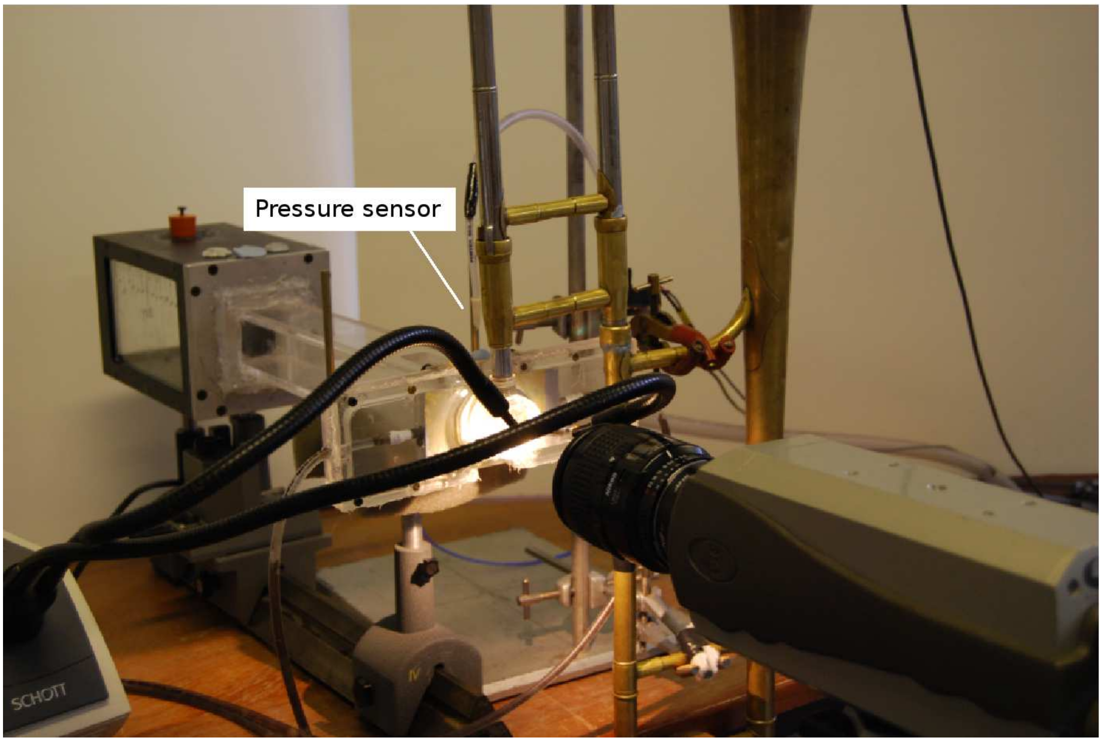


Figure 6.9: *The Sensortechnics HCXM050D6H was inserted just upstream of the artificial lips*

The artificial mouth used for this part of the thesis was that designed by Newton [2008], which is described in detail in section 3.5 of this thesis. In order to measure the pressure in the 'mouth' of the artificial lips a small hole was drilled just upstream of the lips. A small probe was attached to the piece of tubing connected to the Sensortechnics HCXM050D6H sensor and inserted into this hole, as can be seen in figure 6.9.

The artificial mouth was mounted and a trombone was mounted into the system once a playable embouchure was found. The playable embouchure that was found was somewhat lower in frequency than that used with the human musicians. However, the instrument still sounded satisfactorily. Once

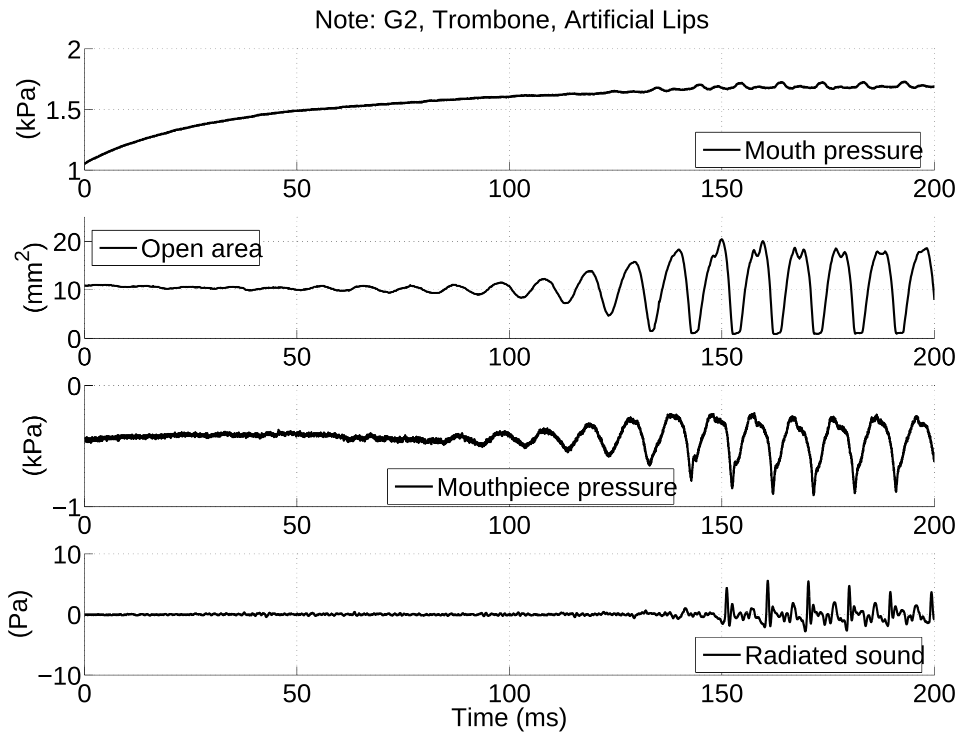


Figure 6.10: *Starting transient for the note G_2 on the tenor trombone. The mouth pressure, lip opening area, mouthpiece pressure, and radiated sound are shown. Player* ***Artificial Lips****, dataset* ***4***

the entire mouth-instrument system was in place the camera was put into place, and all data acquisition software primed for recording.

Unlike human players, the artificial mouth does not have a tongue with which to articulate a note. Instead, a rapid rise in mouth pressure was obtained by another method. The mouth box which the lip system was mounted on has a number of holes in it which in the past have been used to allow the insertion of microphones and pressure sensors. When not being used, these holes are plugged by the insertion of rubber stoppers. It was found that when one of the larger stoppers was removed, air could escape via the mouth cavity instead of being forced through the lips. In this case, there was no longer sufficient

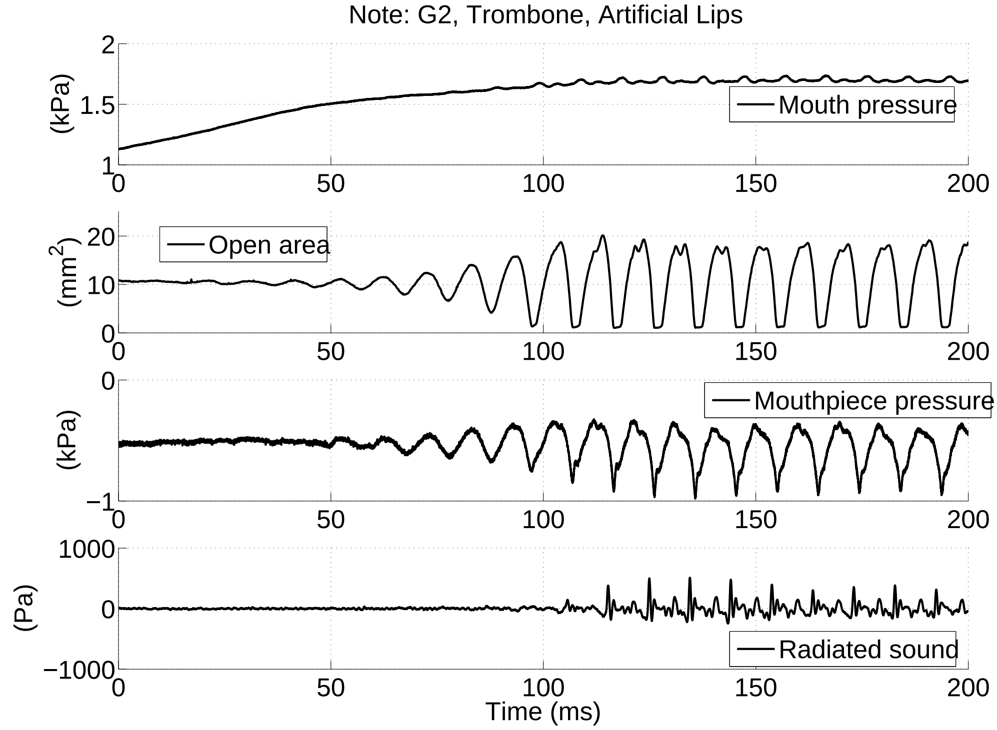


Figure 6.11: *Starting transient for the note G_2 on the tenor trombone. The mouth pressure, lip opening area, mouthpiece pressure, and radiated sound are shown. Player* ***Artificial Lips****, dataset* ***5***

air pressure for the lips to oscillate. This effect was used to create a starting transient on the artificial mouth. First, the air pump was switched on and one of the rubber stoppers removed, preventing the build-up of any air pressure in the mouth cavity. The rubber plug was then rapidly reinserted (by hand), causing a sudden increase in pressure upstream of the lips. This sudden rise in mouth pressure was sufficient to vibrate the lips and hence begin the note. It was found that this method was both simple and repeatable and so it was decided that this would be the method used to replace the 'tongue' of human players.

Figures 6.10, 6.11 and 6.12 show typical recordings of the starting transient

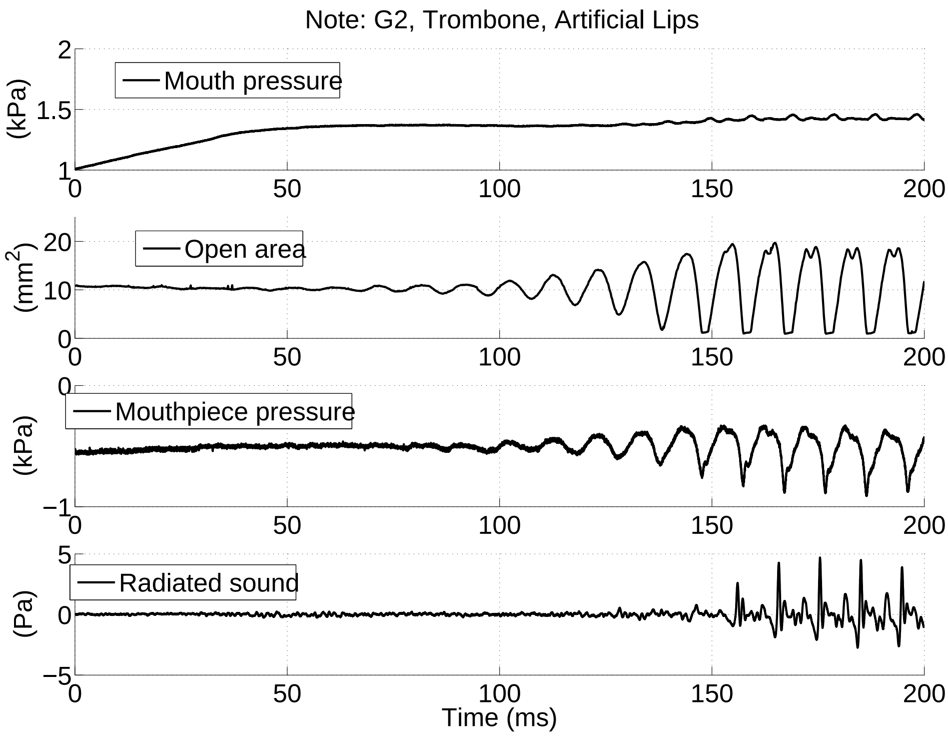


Figure 6.12: *Starting transient for the note G_2 on the tenor trombone. The mouth pressure, lip opening area, mouthpiece pressure, and radiated sound are shown. Player* ***Artificial Lips****, dataset* ***6***

of the artificial lips playing the tenor trombone. It is immediately clear that there are some differences in comparison to the behaviour of the lips of human players. Firstly, the pressure rise in the mouthpiece before the note begins is not constant. There is, initially, a rapid rise in pressure and then a period of slower pressure rise before the note begins. However, replicating precisely the precise form of the pressure rise within the mouth of the player is not entirely necessary. From an acoustic point of view, it matters little the route by which the static overpressure in the mouth reaches the point at which acoustic oscillation of the lips begins. Of course, a complete model must also consider the effect that airflow and turbulence may have on the system using

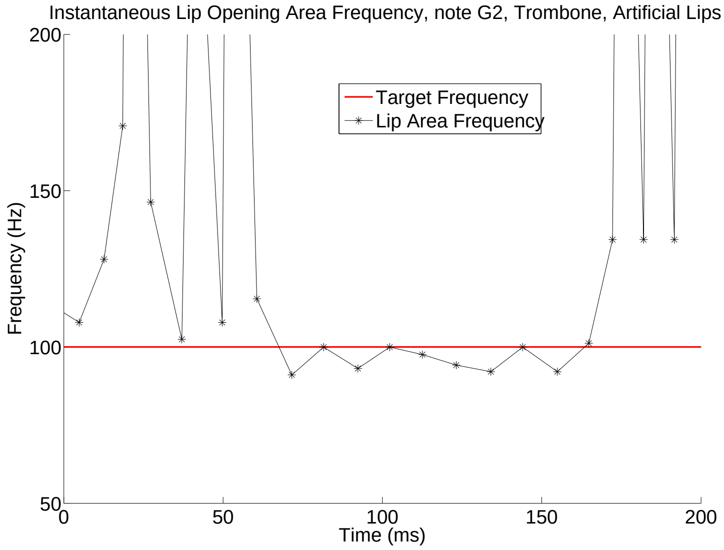


Figure 6.13: *Instantaneous lip opening frequency for the artificial lips calculated using the peak detection software. It is clear from the opening area data for the notes on the artificial lips that there are a number of 'double' peaks. This created a number of 'false positives' when using peak detection to calculate $\overline{\nu}$. This created several large frequency spikes as can be seen here. The peak finding program was altered to use zero crossings, as can be seen in figure 6.14*

the principles of fluid dynamics. However, it seems unlikely that the precise nature of the airflow within the mouth can have more than a secondary effect on the behaviour of the lips and a full treatment of the fluid dynamics involved is beyond the scope of this thesis.

In all three cases, the pressure rises from approximately 1 to 1.5kPa where oscillation appears to begin. This is 1kPa lower than the threshold pressure found using the two human players. However, the artificial lips play at a quieter level than their human counterparts and if one were to measure the transient behaviour of a human player at a *pianissimo* level it would seem likely that one would observe pressures of these amplitudes. Once the note has begun the acoustic component of the mouth pressure has a smaller amplitude

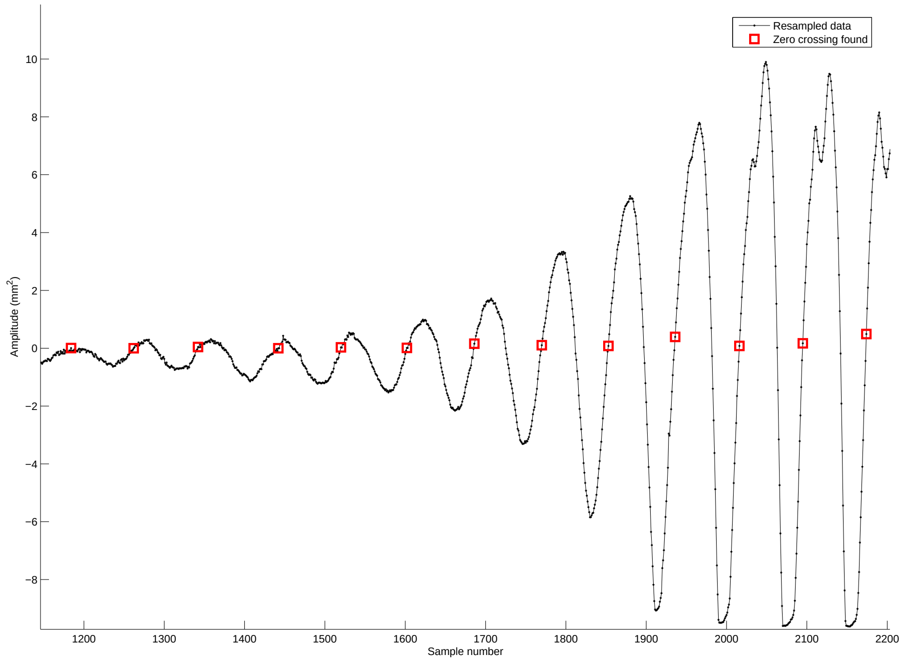


Figure 6.14: *The software used to calculate $\overline{v}$ was altered to find positive zero crossings. This technique was used to avoid the problems caused by the 'double' peaks in the open area data. The zero crossings method relies heavily on a good signal to noise ratio and so the accuracy improves as the amplitude of the motion increases*

than in the case of the human players. This is due to the volume of the mouth being larger in the case of the artificial lips.

However, one of the main purposes of using the artificial lips for this kind of work is in order to ensure consistency and repeatability. In this respect, the artificial lips are clearly successful—all three mouth pressure signals are remarkably similar.

With regards to the lip opening areas, it can be seen that there are several small 'wobbles' before there is any acoustic oscillation in the mouthpiece pressure. This phenomenon occurs because the artificial lips are filled with water and are not as damped as the lips of a human player. Correspondingly,

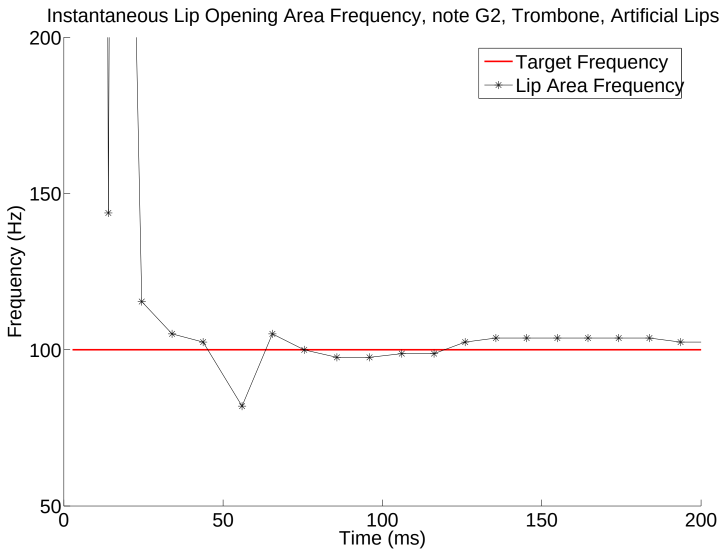


Figure 6.15: *Instantaneous lip opening area frequency $\overline{\nu}$ during the starting transient. Target frequency is the frequency of the target note, with $A = 440$Hz. Note G_2, tenor trombone. Player **Artificial Lips**, dataset **4***

when air begins to flow past them they begin to move, even if there is not yet any sustained self-oscillation. This feature means that it is not practical to use the lip opening area data as a marker of when the note has begun. In addition, the low damping of the lips causes some slightly unusual behaviour of the lip opening area even when the note has reached the steady state. It can be clearly seen that there are some 'double' peaks in the lip opening area for all three recordings. These are caused by the motion of the water in the lips, which causes the lips themselves to move. To produce a truly realistic artificial mouth system it will be necessary to fill the latex lips with something other than water, in order to produce something with mechanical properties closer to that of a real lip.

The unwanted lip 'wobbles' before the note begins proper, coupled with the double peaks that can be seen once the oscillation has begun, meant that

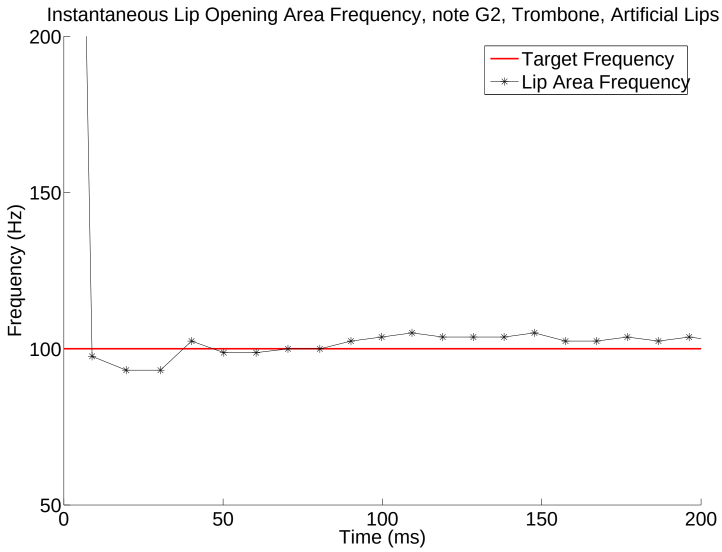


Figure 6.16: *Instantaneous lip opening area frequency $\overline{v}$ during the starting transient. The target frequency is the frequency of the target note, with $A = 440$Hz. Note G_2, tenor trombone. Player* ***Artificial Lips****, dataset* ***5***

it was difficult to obtain much meaningful information from the form of the instantaneous lip opening area frequency when calculated using the peak finding routine, as shown in figure 6.13. The double peaks caused a number of false positives to be found by the software, creating a number of large frequency spikes in $\overline{v}$. To eliminate this problem, the peak finding software (see section 5.5.1) was altered to use a positive zero crossings method as can be seen in figure 6.14. Using the time period between these zero crossings as the 'period' of one oscillation made it possible to recalculate $\overline{v}$. The zero crossings method relies on a good signal to noise ratio and so at the very beginning of the motion, where the lip opening area has a small amplitude, there were still a small number of false positives. However, on the whole the zero crossings method was much more accurate for finding $\overline{v}$ for the artificial lips than the peak finding method.

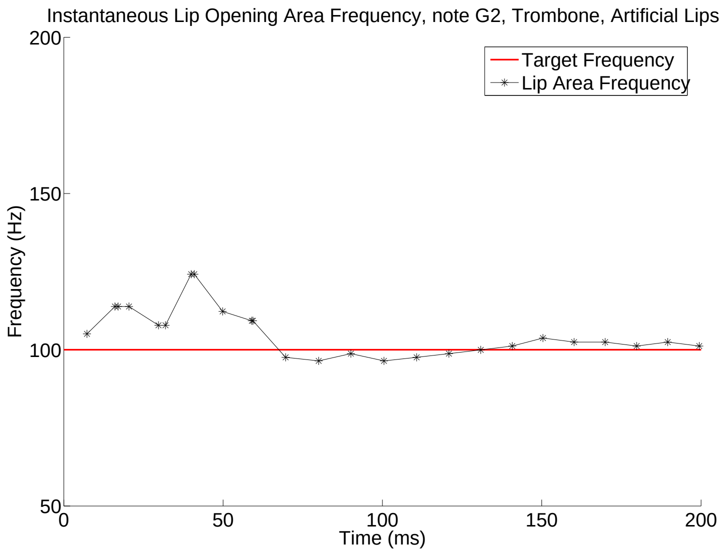


Figure 6.17: *Instantaneous lip opening area frequency $\overline{\nu}$ during the starting transient. The target frequency is the frequency of the target note, with $A = 440$Hz. Note G_2, tenor trombone. Player **Artificial Lips**, dataset **6***

Figures 6.15,6.16, and 6.17 show the recalculated values of $\overline{\nu}$ for the artificial lips during the starting transient. It is clear that on the whole, the artificial lips oscillate at a frequency at, or around, the target frequency, as expected. They appear to maintain a much more stable frequency of oscillation than can be found with human players.

The mouthpiece pressure signals for the notes recorded on the artificial lips are clearly much noisier than the recordings made with human players. There are several reasons for this. Firstly, the artificial lips can not play as loudly as human players, and so when using the low sensitivity PCB microphone to measure the mouthpiece pressure signal the signal-to-noise ratio is correspondingly lower. Secondly, the artificial lips are not trained musicians, and it is not always possible to set up a ‘perfect’ embouchure. It seems that with this particular choice of lip parameters the note that was formed was not ideal. This would appear to be reinforced by the fact that the radiated sound signals are also noisier than their human-played counterparts.

However, that is not to say that the measurements of the starting transient of the artificial lips are not successful. On the contrary, they reinforce the picture which has been obtained with measurements on human musicians. There is an initial oscillation of the lips which creates an acoustic pulse. This pulse traverses the instrument until it is reflected at the bell. Once it returns to the mouthpiece the oscillation receive acoustical feedback and the oscillation is reinforced.

It is also clear that the artificial lips are able to produce starting transients which are both realistic and repeatable and that it will be possible to use them to make a detailed analysis of the starting transient in a way which is not possible with human players. Using the artificial lips, it will be possible to see what effect a change in, for example, mouthpiece pressure has on the starting transient, keeping all other lip parameters constant.

6.3 Conclusions

Measurements were made of the pressure in the mouth of two players during the starting transient and the data compared to that recorded using an artificial mouth. The results obtained were repeatable and consistent with those found for the human players. Several small modifications could be made to the artificial mouth using knowledge obtained from these measurements. These alterations are described in chapter 7.

Chapter 7

Conclusions and future work

'You see, most...most blokes, you know, will be playing at ten. You're on ten here...all the way up...all the way up....You're on ten on your guitar...where can you go from there? Where?'

—NIGEL TUFNEL

7.1 The motion of the lips during performance

The use of a high speed digital camera and specially designed transparent mouthpieces in order to quantitatively analyse the motion of the lips of brass wind instrument players was discussed. It was found that the lips behaved in an asymmetrical manner during the opening and closing phase of an individual cycle. It was found that for some parts of a cycle, the motion of the lips could be described in the form

$$A(t) \propto H(t)^n \tag{7.1}$$

The lips of the human musicians studied tended to open and close along lines of different constant n. There was evidence of hysteresis effects as the lips changed between the different regions of n. With the exception of one possibly anomalous result, $n > 1$. In all cases, the lips closed in a different manner to the way in which they opened. Analysis of the relationship between the opening height of the lips and the opening area provides further support for the findings of Richards [2003] and Bromage [2007]. This information can now be used to create improved computational models of the lips during brass instrument performance. If the lips are modelled as masses on springs then this kind of behaviour could be recreated by altering the value of the exponent n during different parts of the cycle. Improved physical models could be a useful tool for instrument makers and designers.

In contrast to the lips of human musicians, the lips of the artificial mouth were shown to behave in an extremely symmetrical manner. The relationship between opening area and height was examined and it was found that, as in the case of human players, the relationship could be described in the form of equation 7.1. The artificial lips were found to remain on a region with $n \approx 1$ for the vast majority of the cycle. This corresponds to a model of the lips in which the opening area can be described in terms of a rectangle of varying width. Examining the opening width data for the artificial lips confirms this analysis, as the artificial lips open to their maximum width almost instantaneously at the begining of a cycle. At the point of maximum lip opening, the opening and closing phases of the lip motion are indistinguishable.

7.2 Extremely loud playing

7.2.1 Variations in mouthpiece and radiated sound pressures with amplitude

The pressure in the mouthpiece of a tenor trombone and a horn was measured during both brassy and non-brassy playing using a low sensitivity PCB pressure transducer. The results were consistent between players, instruments, and pitch. In general terms, the form of the pressure signal did not show any significant changes—other than that of amplitude—between non-brassy and brassy playing. The main difference between the two cases is the variation in the maximum rate of change of pressure in the mouthpiece $(\frac{\partial P_m}{\partial t})_{max}$. This is consistent with the theory of nonlinear propagation as proposed by Hirschberg *et al.* [1996].

The corresponding radiated sound pressures were also recorded. Examining the form of these pressure signals showed that an increase in mouthpiece acoustic pressure amplitude of factor 2 or 3 led to an increase in radiated acoustic sound pressure ampitude of factor 10 or more. In addition to this, there is a clear variation in the form of the radiated sound for brassy and non-brassy playing. In the brassy case, there is clear evidence of shockwave formation within the body of the instrument. The non-brassy case does not behave in this manner.

Spectral centroids were calculated for both mouthpiece and radiated pressures during both brassy and non-brassy playing. It was shown that the centroid of the radiated sound increased by a much greater factor than the centroid of the mouthpiece sound when changing from non-brassy to brassy playing dynamic.

Three recordings of non-brassy playing were used to calculate the linear high-pass filtering effect of the bell. Applying this filter to a brassy mouthpiece recording made it possible to calculate the expected spectral centroid at the output if the instrument were treated in an entirely linear manner. Comparing this calculated centroid with the measured, nonlinear, centroid showed that the majority of increase in the energy levels of the higher harmonics should be attributed to the nonlinear properties of the instrument.

It now seems clear that the distinctive brassy or 'cuivré' sound of a brass wind instrument is primarily due to the nonlinear properties of the instrument itself. It is of interest to brass musicians, makers, and historians to be able to classify instruments into distinct groups. If it is the shape of the instrument which dictates the way the instrument performs in the brassy regime then it would seem sensible to use brassiness as a form of musical taxonomy, and, indeed, some researchers have already begun this task [Gilbert *et al.*, 2007]. In addition, if a brass instrument maker wishes to make an instrument which sounds either more or less brassy than an existing design then he will be able to add either cyclindrical or conical sections as necessary. Cylindrical bore profiles will create a brassier sound whilst conical bores will counteract the effect. With regards to performance, if musicians are able to alter the maximum rate of change of pressure in the mouthpiece then they will be able to either lessen or enhance the nonlinear wave steepening [Norman *et al.*, 2009]. In other words, they will be able to control the level of brassiness without changing dynamic. If musicians are able to master this technique then they will be able to add a considerable variety of timbre to their musical palette.

7.2.2 Variations of lip opening area with amplitude

Lip opening areas were recorded using a high speed camera for a number of notes, instruments, and players. The opening area increased in size with amplitude and decreased with pitch. Other than these expected variations there are no dramatic differences to be seen between brassy and non-brassy pairs.

7.2.3 Variations of lip motion in the direction of the air flow

A specially designed trombone mouthpiece with side window was made in order to study the motion of the lips in the longitudinal direction—that is, in the direction of the airflow (the $y - z$ plane). Three different trombone players were asked to play pairs of notes of the same pitch but different dynamic level; one at a *mezzo forte* level and a second as loudly as possible.

Inspection of the videos and pressure signals obtained using a high speed camera and microphones—shown in section 4.8—makes it clear that during brass instrument playing the lips of the player undergo a complicated motion in all three dimensions. The top lip dominates the motion and appears to traverse an approximately elliptical path, protruding into the mouthpiece in the direction of the airflow whilst arcing upwards towards the roof of the mouthpiece. Then, it travels back towards the face of the player whilst dropping back down to its initial vertical position. This is in agreement with the results of Copley and Strong [1996] and also of Newton [2008]. Analysis shows that the top lip can travel as far as 1cm in both horizontal and vertical directions.

In agreement with the results shown in both chapter 3 and Bromage [2007] the amplitude of the lip motion increased with amplitude but also decreased with pitch. For some low frequency, non-brassy, playing the distance which the lip moved was greater than the distance during higher frequency, brassy, playing. This suggests that it is not the amplitude of the motion of the top lip in the longitudinal direction that is primarily responsible for the brassy sound.

Inspection of the mouthpiece pressure signals in comparison with the corresponding high speed camera footage suggests that even though there is a large mass of the top lip moving throughout the cycle the motion of this mass does not appear to contribute significantly to the pressure in the mouthpiece. If this is the case, to produce a realistic model of the lip-reed it may not be necessary to fully reproduce the full three-dimensional motion of the lips.

7.2.4 Obtaining the brassy sound using an artificial mouth

An unsuccessful attempt was made to use the artificial mouth—detailed in section 3.5—to produce a brassy sound. The current design of the artificial mouth is not yet capable of producing self-sustained oscillations at the *ffff* level. Some design modifications—or possibly a complete redesign—are required in order to successfully obtain the desired effect. During a *crescendo* on a brass instrument the player continually makes adjustments to the embouchure. In order to produce a realistic *crescendo* using the artificial mouth this kind of fine control of the lips during playing must be achieved. This should be possible with some kind of material whose tension can be controlled using an electrical signal. However, the first aim should be to produce not a crescendo, but instead to concentrate on achieving the ‘brassy’ sound using the artificial mouth. An air source capable of producing pressures in the kPa range is required. An investigation of the precise embouchure used by human players at the loudest level (geometry, tension) should yield enough information to allow the artificial lips to play at a brassy dynamic.

7.3 Transient behaviour of the lip reed

7.3.1 Starting transients

The lip opening area, pressure in the mouthpiece and sound radiated from the bell of the instrument were synchronised and measured during the starting transient for a variety of instruments and musicians. Overall, the behaviour was consistent between musicians but there were differences in the precise nature of the starting transient for both different musicians and different instruments. The musician begins the note by causing the lips to oscillate at a frequency close to that of the desired note. This creates an acoustic pulse which travels through the instrument and is partially reflected at the bell. When this reflected wave reaches the mouthpiece the oscillation is reinforced and the amplitudes of the mouthpiece pressure and lip opening area increases dramatically. The starting transient is greatly influenced by the time delay between the beginning of the lip oscillation and the return of the initial pulse to the mouthpiece of the instrument. The data obtained will allow comparisons to be made between physical and computational models of the lips and the behaviour of the lips of human players.

Measuring the lip opening area, mouthpiece pressure signal and radiated sound makes it possible for musicians, instrument makers, and scientists to make a qualitative statement about the quality of an instrument. For instance, it should be possible to diagnose a valve misalignment by carefully studying the form of the transient and comparing with that of a known 'good' instrument. Comparing two nominally identical instruments in this manner should make it easier to find specific differences between them. Being able to quickly and accurately find the difference between a good instrument and a poor one in this way could be a useful form of quality control for instrument makers.

7.3.2 Slurs

The technique used to measure and analyse the starting transient was also applied to a number of lip-slurs performed on the horn. It was found that the time taken for the system to change from one steady-state to another was around twice that for the system to reach steady-state during the starting transient. Different musicians appear to use different techniques for playing a slur and some evidence of this could be seen in the results. If different techniques and practice regimes can be shown to have a measurable effect on the sound of a slur then it may be possible to offer some advice to musicians with regards to producing a specific effect. However, the research presented here is still very much preliminary and it may be some time before scientists are able to help teach musicians.

7.4 Mouthpiece pressures and transient behaviour of an artificial mouth

A small absolute pressure sensor was used to measure the pressure in the mouth of several human musicians during the starting transient. It was found that during the starting transient, the pressure in the mouthpiece increased steadily until sustained self-oscillation began. The pressure in the mouth during self-oscillation was found to be, as expected, π radians out of phase with the mouthpiece pressure. Using this information, the pressure in the artificial mouthpiece was adjusted to try and create a realistic starting transient. In general terms, the lips of the artificial mouth reinforce the data taken from human musicians; the lip oscillation and mouthpiece pressure are reinforced by acoustic feedback from the air column within the instrument. The lips of the artificial mouth are not as heavily damped as those of human players, and this accounts for some of the features of the starting transient of the artificial mouth. The results are consistent from measurement to measurement, suggesting that, with some small modifications, the artificial mouth will be of great use in further studies of the starting transient.

7.5 Future work

7.5.1 The motion of the lips during the steady-state

The current analysis technique is, on the whole, very successful for quantitative measurement of the motion of the lips. However, the 'binary' video analysis method relies on good contrast and lighting of the lips during recording. In addition, the teeth of the player can make it difficult to extract the 'true' opening area. An alternative analysis method—perhaps using edge detection—could be a useful tool for future studies.

The calculated values of the height-area parameter n can now be used in physical and computational modelling. For human players, there are at least two different values of n during a typical cycle and perhaps existing models can be adjusted to use different n at different points during the simulation.

Since the lips close in a different manner to how they open perhaps some asymmetry could be introduced, perhaps by altering the value of the spring constant when the lips have reached their maximum opening.

7.5.2 Extremely loud playing

Some brass players report being able to alter the 'brassiness' of a note at constant pitch and volume [Norman *et al.*, 2009]. One factor which determines the nonlinear distortion in brass wind instrument playing is the maximum rate of change of mouthpiece pressure, $(\frac{\partial P_m}{\partial t})_{max}$. If the player can somehow alter the lip motion then it may be possible to change the pressure rise in the mouthpiece and thus alter the brassy sound. However, since this effect has not been observed here it seems that this may be a special technique available to some players as opposed to a more general phenomenon. Further investigation in this area would be of great interest.

Some attempts have already been made to use the 'brassiness' of an instrument as a form of musical taxonomy [Gilbert *et al.*, 2007]. The results presented here further confirm the theory that the brassiness of an instrument is created by the instrument itself, not by a constriction of the lips. With this in mind, it is logical to try and remove the human element from further brassiness studies. The input from a human player to the instrument is approximately sinusoidal. Attaching an instrument to a loudspeaker of suitable power output it will be possible to measure the nonlinear distortion of a sine wave as it propagates through the instrument. Removing the human element from the procedure will simplify the process of classifying instruments by their nonlinear properties.

7.5.3 Transients

The work presented here is still preliminary and there are several possible avenues for further exploration of the starting transient of the brass wind instruments. Firstly, it is vital to gain an understanding of how consistent an individual player is on repetitions of the same note. Ideally, one would obtain hundreds of measurements of a single player playing the same note in the same manner, and then repeat these measurements across multiple players at skill levels varying from beginner to professional. Once a large number of measurements have been obtained then it will become easier to distinguish which behaviours are player specific. A study of what exactly happens when a player 'splits' a note would be particularly interesting.

One of the reasons for studying the starting transient is because musicians typically use the 'attack' of an instrument as a way of distinguishing good instruments from bad. Once the desirable transient behaviour of a particular musician has been obtained using measurements on a 'good' instrument it should then be possible to see what differences there are when they play on a 'bad' one. It would also be interesting to modify instruments to simulate defects; to see, for example, what effect the misalignment of a valve may have on the starting transient.

During a slur a player typically does more than just alter the embouchure. Unless the destination note is also a resonance of the current air column of the instrument it will be necessary to change the instrument length, either by activating or deactivating a valve or altering the position of the slide. It would be interesting to measure the precise time and speed at which this change takes place. This could be done using a small mechanical sensor, or a sensing device such as a laser vibrometer. It may also be of interest to study the pressure in the instrument at particular points during the slur, perhaps using the multiple microphone technique used in APR to separate forward and backward going waves.

7.5.4 Transient behaviour of an artificial mouth

There is clearly great scope for the use of artificial mouths in the study of the transient behaviour of brass instruments. The current mouth, however, requires a few minor modifications before it can be used to produce truly realistic simulations. Firstly, the current air supply is not powerful enough to produce notes at anything more than a *pianissimo* level. A more powerful supply of compressed air would be an obvious first step. Secondly, in normal instrument playing brass players use their tongue to articulate the note which they wish to produce. The current artificial mouth does not have any kind of tongue. Producing a realistic tonguing system would be of great help in producing more realistic transient behaviour. The use of a solenoid to operate the 'artificial tongue' would also make it possible to measure precisely the moment at which the note began, or to control the precise speed and velocity of the note articulation.

With these modifications, and in conjunction with more numerous measurements of human players it should then be possible to use the artificial mouth to study the differences between different instruments with the knowledge that any variations in the transient behaviour must be due to differences between the two instruments.

7.6 Final conclusions

The aim of this thesis was to measure, analyse, and quantify the behaviour of the lips of brass wind musicians during a variety of playing situations. Examination of the lip opening area during the steady state has shown that the motion of the lips cannot be described in a simple manner. The relationship between the lip opening height and the lip opening area seems to be particularly complex and different stages of the cycle will need to be treated differently when it comes to precisely reproducing this behaviour using computational models.

When a brass wind instrument is played loudly it produces one of the most distinctive timbres in the musical world. Until recently acousticians were not sure whether or not a constraint of the motion of the lips was a factor in producing this unique brassy sound. However, it has become accepted that the primary cause of this increase in energy of the higher harmonics is nonlinear propagation and wavefront steepening within the bore of the instrument. The work presented in this thesis provides strong experimental evidence to support this position.

The starting transient is an extremely important feature of almost any musical sound. However, research into the acoustics of the brass winds has tended to concentrate on the behaviour of the steady state. This thesis has built upon some preliminary work by Bromage [2007] to produce an experimental method for quantifying the behaviour of the lip-instrument system during the starting transient. Whilst research is still at an early stage there is now enough data to help create realistic computational simulations of the starting transient. More experimental work in this area will further increase the accuracy of physical modelling of the lips and could well make it possible to assist instrument makers with instrument design, manufacture, and quality control.

Appendix A

Lip motion in the $y - z$ plane during extremely loud playing

Figures A.1 and A.2 show a complete cycle of the lip-motion in the $y - z$ plane for both *mezzo forte* and *ffff* playing of the note F_3 by player JG on the tenor trombone. Figures A.3 and A.4 show the same information, but for player MF whilst figures A.5 and A.6 display the note $B\flat_1$ (the pedal note) played by player JG.

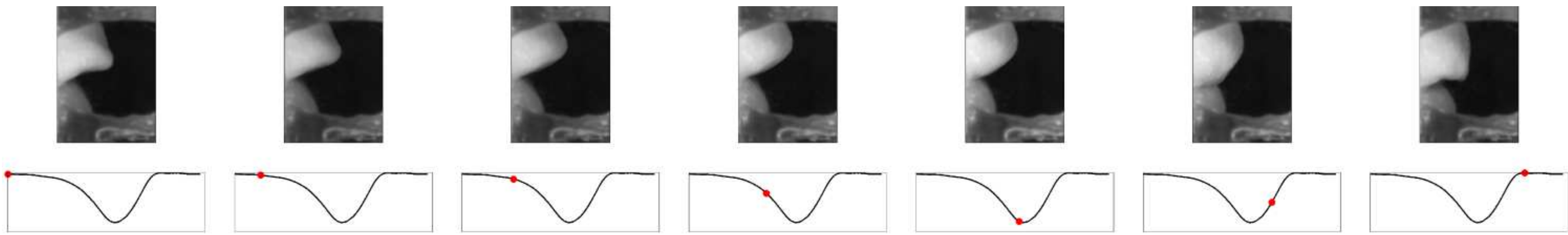


Figure A.1: *A complete cycle of the lip motion for the note* F_3 ***played at*** **mf** ***by player JG*** *as viewed from the side. The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

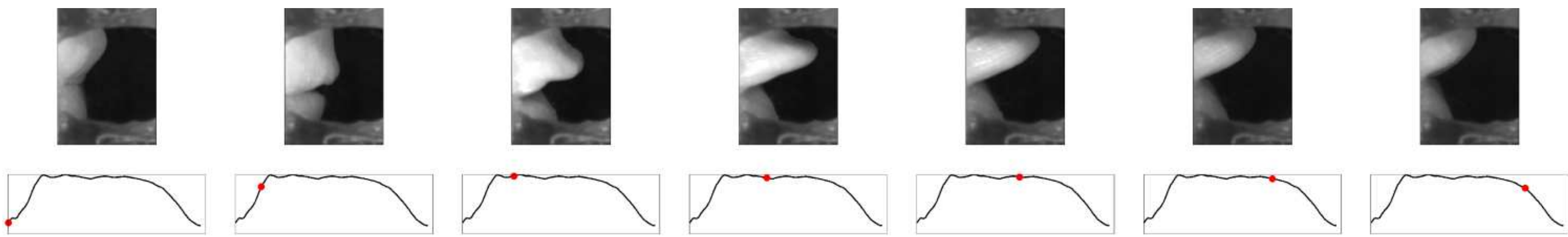


Figure A.2: *A complete cycle of the lip motion for the note* F_3 ***played at*** **ffff** ***by player JG*** *as viewed from the side. The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

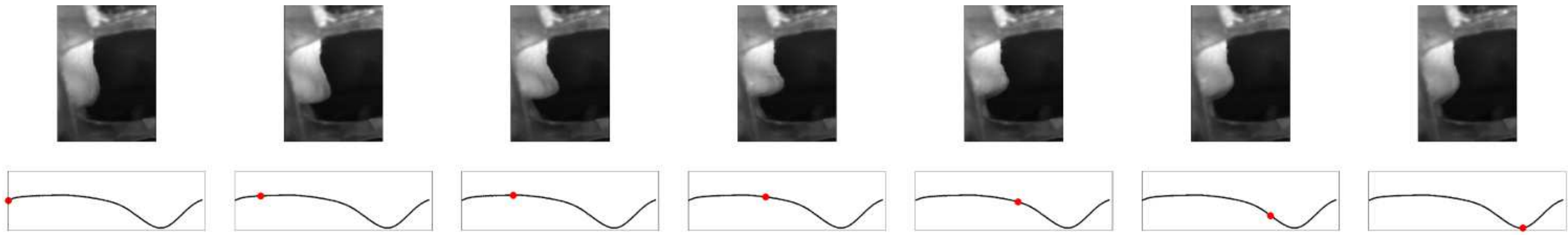


Figure A.3: *A complete cycle of the lip motion for the note F_3 **played at*** **mf** ***by player MF** as viewed from the side . The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

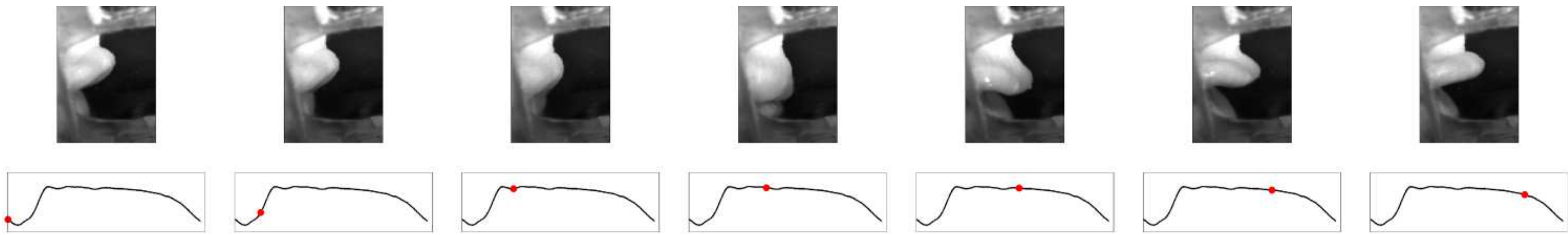


Figure A.4: *A complete cycle of the lip motion for the note F_3 **played at*** **ffff** ***by player MF** as viewed from the side. The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

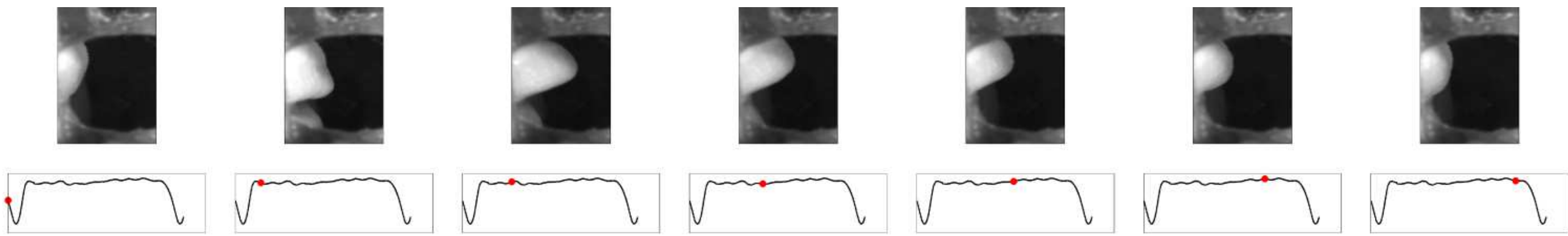


Figure A.5: *A complete cycle of the lip motion for the note* ***B♭$_1$ (pedal) played at*** **mf** ***by player JG*** *as viewed from the side. The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

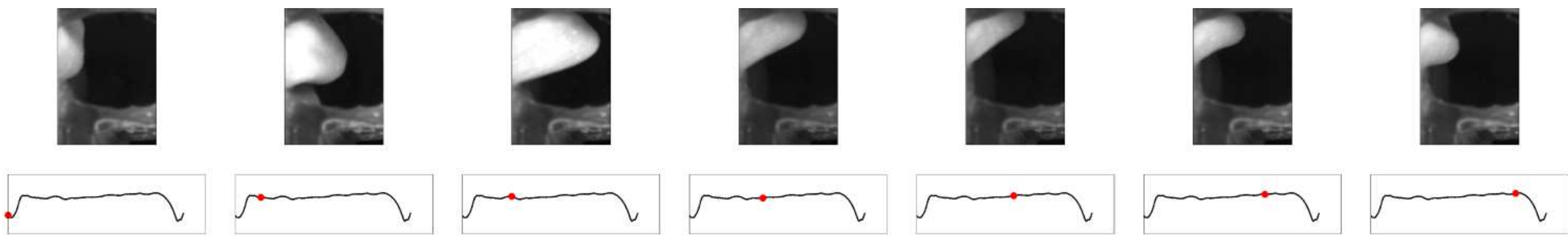


Figure A.6: *A complete cycle of the lip motion for the note* ***B♭$_1$ (pedal) played at*** **ffff** ***by player JG*** *as viewed from the side. The corresponding mouthpiece pressure signal is shown below. The red dot indicates the point in the cycle corresponding to the image above*

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