STUDY OF THE LIP REED DESTABILISATION USING AN ARTIFICIAL MOUTH

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1. ABSTRACT

The reed mechanism of a wind instrument driven by an oscillating pressure on the instrument side can be defined as having an inward (sliding door) or outward (swinging door) behaviour. In the case of a brass instrument there is no clear inward or outward behaviour as there is in the case of an instruments such as the clarinet but rather a combination of the two modes, with the lips showing a greater affinity to one type of behaviour or the other depending on the playing situation.

Using an artificial mouth to play a trombone and a telescopic tube, mechanical response measurements have been done to determine which type of behaviour is more predominant for various playing parameters. Mechanical response measurements enable the frequency and phase behaviour for the lip resonances to be measured both with and without a mouth pressure applied. These measurement are compared to those obtained using computational simulations of a 2 mass model. Using these results it is possible to understand how a brass player can "lip" the pitch of a note played on the instrument above or below the acoustical resonant frequency of the instrument.

2. INTRODUCTION

The behaviour of a brass players lips cannot be simply classified into one of the two oscillatory regimes for reeds, inward and outward striking, as defined by Helmholtz [11]. Experimental work has shown that the lips of the brass player seem to act as both inward and outward striking depending on the playing situation [4] [6] [12]. This can be seen by the ability of a brass player to play the instrument such that the note produced can have a frequency which is either above or below the acoustic resonance frequency of the resonator (instrument). By considering the players lips as a simple driven harmonic oscillator [3] [8] [13] it can be seen that playing above or below the acoustic resonance frequency corresponds to different reed behaviour. Cullen [5] showed using a single mass model for the lips, that when the playing frequency is clearly below that of the acoustic resonance of the instrument the lips are acting like an inward striking reed whereas they act like an outward striking reed when the playing frequency is above the acoustic resonance frequency.

In the region between playing well above and well below the acoustic resonance frequency of the instrument, the behaviour of the lips cannot be clearly represented by either a purely inward or outward striking reed type. By measuring this difference in frequency between the acoustic resonance frequency and the playing frequency of an instrument the type of reed behaviour can be determined but only when there is a clear difference between these two frequencies. If the playing frequency and the acoustic resonance frequencies are in close proximity this method becomes unreliable. To overcome this problem the response of the lips to a set driving frequency can be measured. Analysis of the magnitude and phase response of the lips driven over a range of frequencies leads to a more accurate understanding of the of the lip properties.

The following work shows some experimental results showing the reed type, taken by measuring the mechanical response of the artificial lips to an applied acoustic pressure. These mechanical response measurements can be compared to results given by using a computational two mass model of the lips. This then leads to a discussion of the lipping of notes by a brass player.

3. EXPERIMENTAL SETUP AND PROCEDURE

The experimental measurements are done using an artificial mouth as used by Cullen [5] and based on a design by Gilbert and Petiot [10]. This artificial mouth is used to play a telescopic pipe which can be extended over a range of 1.0 to 2.3 meters, with a trombone mouthpiece attached to one end. The use of the artificial lips enables a fixed lip setting to be sustained over a large number of experiments and also facilitates easy measurement of the lip opening.

The experimental setup can be seen in Figure 1, the artificial mouth is mounted on an optical bench and a laser beam is expanded down the length of the tube and between the lips. This beam is then focused onto a photo diode which gives a voltage directly proportional to the incident light intensity, which in turn is proportional to the lip opening height. Signals from the photo diode and from a miniature microphone placed just behind the lips are sampled and stored on a computer for analysis.

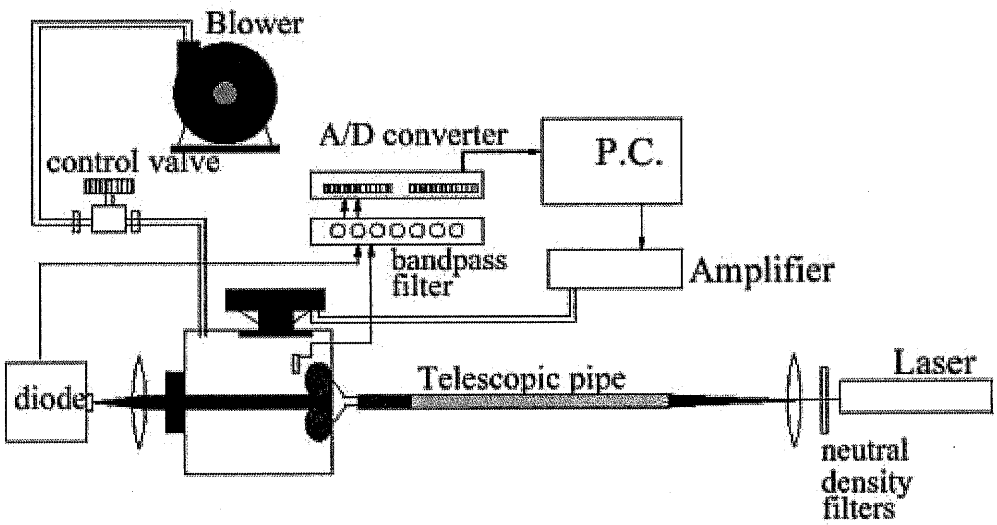

Figure 1: *The experimental setup for mechanical response measurements.*

The mechanical response is measured by creating an acoustic pressure in the mouth cavity using a loudspeaker mounted on the top of the artificial mouth. This acoustic pressure is measured by a small microphone placed just behind the lips. The amplitude and phase response of the lips are measured over a range of driving frequencies between 50Hz and 600Hz. By measuring the mechanical response with no pressure difference across the lips and also with a pressure which is just below the threshold pressure at which there is an onset of auto-oscillation, the lip frequencies responsible for the destabilisation of the lips can be found.

The amplitude of the mechanical response is calculated as shown in equation 1, and the phase response is give by equation 2.

$$C(\omega) = \frac{h(\omega)}{P_m(\omega)} \tag{1}$$

$$\angle C(\omega) = \angle h(\omega) - \angle P_m(\omega) \quad (2)$$

Where h(ω) is the separation of the lips and $P_m(\omega)$ is the alternating component of the mouth pressure.

By examining the conditions under which there is a supply of energy by the reed mechanism and the oscillation properties of forced simple harmonic oscillators [3], it can be seen that for an inward striking reed ∠C(ω) = π/2 and for an outward striking reed ∠C(ω) = -π/2. Using this, peaks in the mechanical response amplitude curves, which show the resonant frequencies of the lips can be specified as inward or outward striking by their phase response. Thus in the example response measurement shown in figure 2 the first peak at 135Hz is an outward striking resonance and the second peak at 155Hz is an inward striking resonance.

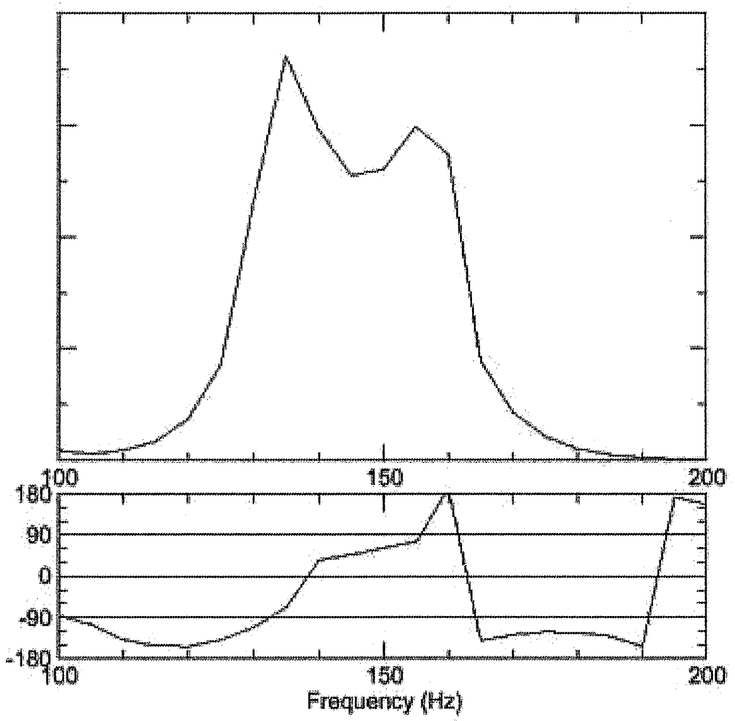

Figure 2: *Mechanical response measurement of the artificial lips.*

4. RESULTS

The first set of results (figure 3) shows the playing frequency as a function of the pipe extension. This is measured by setting the artificial lips and extending the length of the tube in steps from 1.3 meters to 2.2 meters. The lip resonance frequencies as given by a mechanical response measurement are shown by the horizontal lines, and the acoustic resonance of the pipe at the different pipe lengths is given by the dotted line, as measured using an input impedance rig at the University of Edinburgh [2].

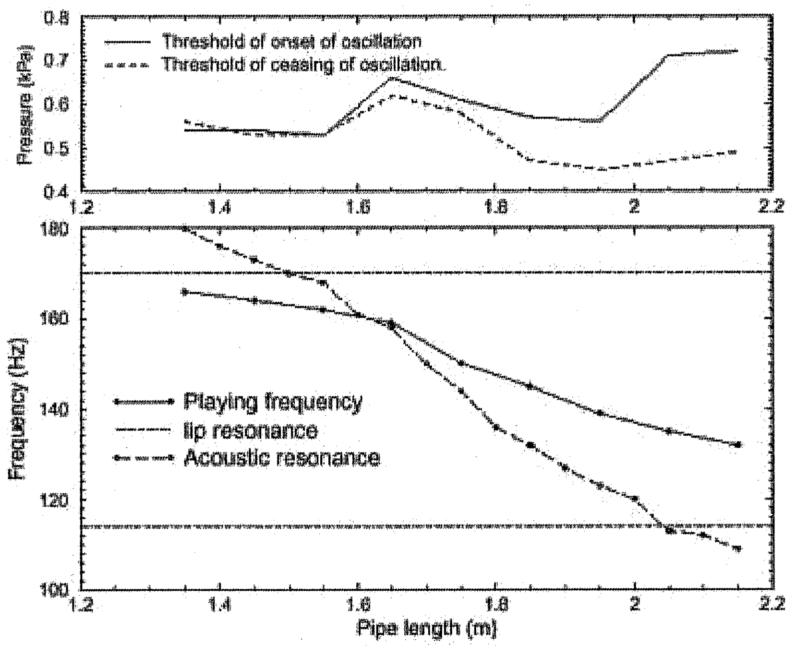

Figure 3: *Playing frequency against pipe length.*

It can be seen from this graph that at the shorter pipe lengths the playing frequency is below both the acoustic resonance frequency of the pipe and the upper lip resonance which has an inward striking characteristic. This is consistent with the lips acting as an inward striking reed. For the longer pipe lengths the playing frequency is above the acoustic resonance and the lower outward striking resonance of the lips. This is consistent with the lips acting as an outward striking reed. It can also be seen that there is a smooth transition between these two different regimes. In order to understand something of what is happening in this area mechanical response measurements where made at each of the pipe extensions.

Figures 4 shows a set of mechanical response measurement for pipe lengths of 1.35m, 1.55m, 1.65m and 1.95m. The graphs show the response with no mouth overpressure (solid line) and with a mouth overpressure just less than the threshold pressure (dotted line). Also shown is the playing frequency (solid vertical line) and the acoustic resonance frequency of the pipe (dotted vertical line).

The lip frequency which is most important for a played note can be seen by comparing the response measurements with and without mouth pressure applied. As the threshold pressure is approached the amplitude response of one of the peaks grows until it destabilises and auto oscillation occurs. By examining the phase response of this lip resonance it can be seen whether the lips are acting more as an inward or outward striking reed.

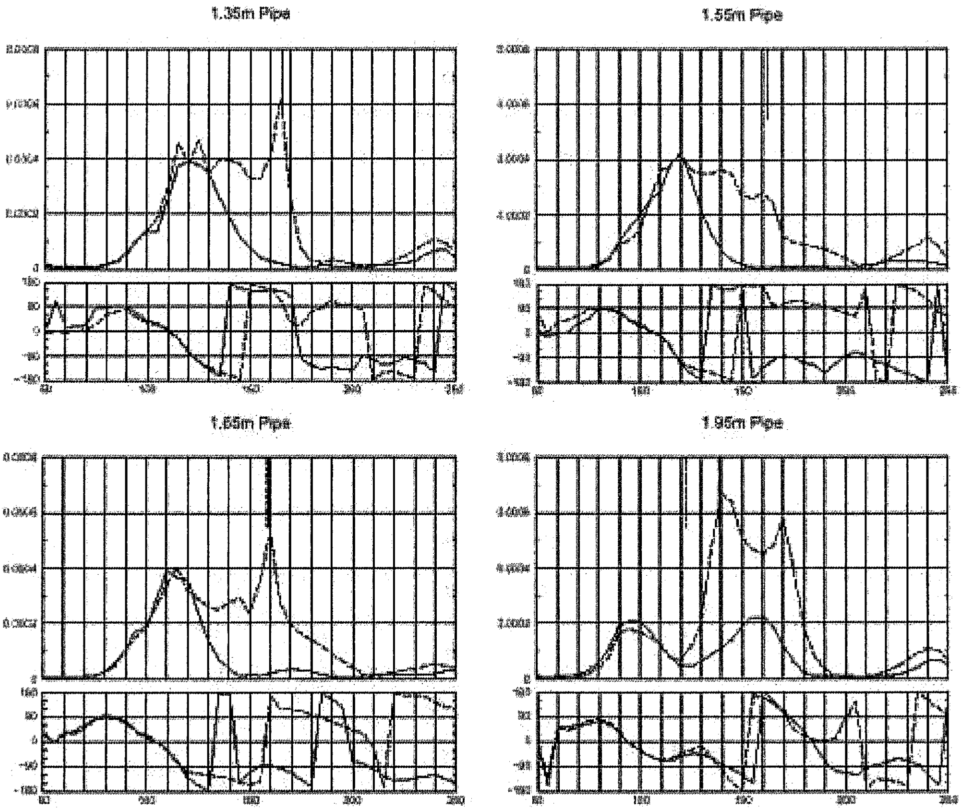

Figure 4: Mechanical response for different pipe lengths

For the case of the 1.35 meter pipe it can be seen that the destabilising lip resonance at 165 Hz has a phase response of $+\pi/2$ and so the lips are acting as an inward striking reed, which is consistent with the analysis of figure 3. For the case of the 1.95 meter pipe the destabilising lip resonance has a frequency of 140 Hz and a phase response of $-\pi/2$. This means that the lips are acting as an outward striking reed. For the case of the 1.55 meter and 1.65 meter pipe lengths where the playing frequency is very close the acoustic resonance of the pipe the reed behaviour is much less clear. In both of these cases the phase response has a value which is close to π. This suggests that there is no longer a clearly inward or outward striking behaviour of the lips but rather there is some coupling between the two different lip resonances.

5. GENERIC 2-MASS MODEL

The threshold behavior shown in figure 3 can be computationally reproduced using a two-mass model of the lips. The model used here is based on a simple one-mass model proposed by Cullen [6][5], taken into two degrees of freedom by summing the motions of two such oscillators. This provides a very simple system that encompasses the basic characteristics of a two-mass model.

$$\frac{d^2x_i}{dt^2}+\frac{\omega_i}{Q_i}\frac{dx_i}{dt}+\frac{1}{\mu_i}\frac{d\psi}{dt}+\omega_i^2(1+C_i)x_i-C_i\omega_a^2x_j=\frac{\left(p_m-\frac{\rho\overline{V_1}^2}{2}\right)}{\mu_i} \qquad (3)$$

Here, we use the coupling constant C_i to denote the strength of the coupling spring between the two masses. The variable μ_i provides the coupling coefficient between the mass and the volume flow, where:

$$\frac{1}{\mu_i} = \frac{1}{(1/\mu_{out} - 1/\mu_{in})}; \tag{4}$$

μ_{out} is the ``outward striking" coupling coefficient, and $\mu_{in}$ is the ``inward striking" coupling coefficient. These two parameters are directly proportional to the mass of each oscillator and inversely proportional to the appropriate surface area of that oscillator. For the inward striking coefficient, the surface area is equivalent to the area of the lip parallel to the flow. For the outward striking coefficient, the surface area is equivalent to the area of the lip normal to the flow - i.e. the effective lip area inside the mouth. The inward striking motion therefore has a negative value of $1/\mu_i$, and the outward striking motion has a positive value. It is worth mentioning that due to the incredible simplicity of this model, these parameters may well be only loosely related to their real-world counterparts. Attempting to obtain accurate values from experimental observations is perhaps less useful than trying to fit the parameters to give the desired behaviour from the model.

We also have the linearised equation for the acoustical resonator:

$$\frac{d^2\psi}{dt^2} + \left(\frac{\omega_a}{Q_a} + \frac{Z_a\omega_a}{Q_a}\frac{b\overline{H}}{\rho\overline{V_l}}\right)\frac{d\psi}{dt} + \omega_a^2\psi - \frac{Z_a\omega_a}{Q_a}b\overline{V_l}(x_i + x_j) = 0 \tag{5}$$

Here, Z_x is the input impedance of the resonator, H is the constant part of the lip separation, and V_l is the constant part of the fluid flow velocity through the lips. Note that this equation represents a resonator with only a single resonant mode. This is only valid for near-threshold situations, where we are currently looking. In order to investigate the threshold behaviour at different modes, we can simply alter the resonance frequency and quality factor appropriately, using values from known impedance curves of an instrument. Indeed, this analysis can show us at what resonator length the natural playing mode changes - by looking at the point where the threshold pressure for one mode becomes lower than another.

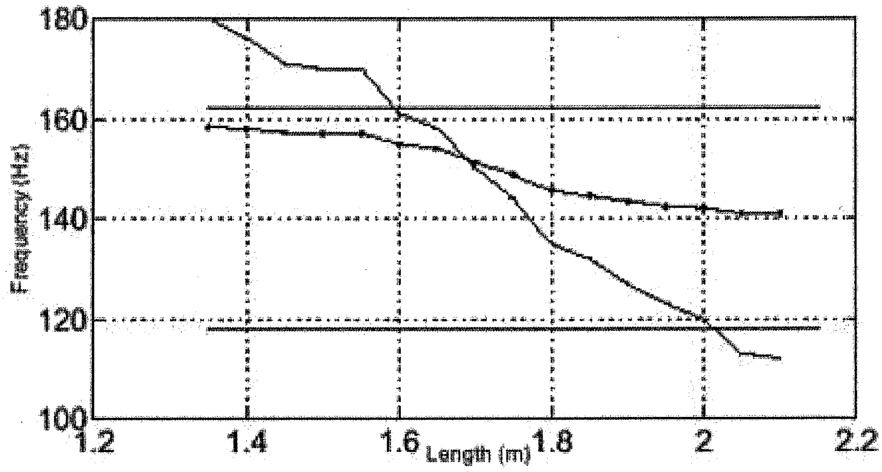

Figure 5: *Threshold frequency as a function of tube length.*

One can, using linear stability analysis [5], obtain the threshold parameters as a function of resonator length, as shown in figure 5.

This graph has a similar form to experimentally obtained results shown in Figure 3. The values of the playing frequencies can be adjusted easily by tweaking the model parameters. Specifically, the lip resonances ω_i and the coupling coefficients μ_i. This is equivalent to adjusting the embouchure of the human player or artificial mouth.

These results show one solution to a problem encountered by many previous, one mass, models - the ability to play above, below and directly on the instrument resonance. An inward or outward striking one-mass model will play only below or above the instrument resonance respectively [6].

6. APPLICATION TO ``LIPPING" NOTES

The above results clearly show that the lip resonance frequencies have the effect of pulling the note away from the acoustic resonance frequency of the instrument. Although the work shown here is for a fixed lip setting with the acoustic resonance of the instrument being varied, due to the experimental difficulties in controlled variation of the lips. An equivalent analogy can be drawn to the case with a fixed acoustic resonance and variation of the lip parameters.

The brass player has the ability to change a large number of the parameters which affect the frequency of the lip resonance modes. For example if a player is plays a note which has a frequency which is in close proximity to the acoustic instrument resonance, it can be seen from the above results that there must be a strong coupling between two of the lip resonances with opposite reed type behaviour. If the player is to then change their lip resonances so that the inward striking lip resonance becomes more predominant then the frequency of the played note would change so as to become lower than the acoustic instrument resonance frequency. If the player changes their lip resonances so the that outward striking lip resonance becomes more predominant then the opposite would happen and the playing frequency would be raised above the instrument resonance frequency.

7. CONCLUSIONS AND FURTHER WORK

Experimental measurement shown a clear transition between inward and outward striking reed behaviour as the acoustic resonance of the instrument is changed with respect to the lip resonance frequencies. In the area where the playing frequency is well above or well below the acoustic resonance the lips behave as predominantly outward or inward striking reeds. In the region between this there is a more complicated behaviour where coupling between the different lip resonances becomes important.

Mechanical response measurements provide a method of viewing how the coupling between the different lip modes is affected by parameters such as the acoustic resonance. These methods can also be used to study effects of the mouth resonances on the played note.

The two-mass model shows that the characteristic "lipping" behaviour seen here is easily explained by using an appropriate two-mass model of the lips. However, the model used here is highly simplified, and rather abstract. As such, it cannot predict much of the important behaviour of real lips - such as collisions and high amplitude behaviour. The mathematical ideas still apply to other two-mass models - especially those proposed by Adachi and Sato [1] and Federico [7]. These models can be further improved by the use of two separate resonant frequencies, rather than the single degenerate frequency proposed previously.

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