USE OF EXPERIMENTAL STUDIES IN DETERMINING A TWO-MASS LIP MODEL

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ABSTRACT

Several two-mass models of the lips have been proposed in recent years. This paper examines the fundamental behaviour of a two degree of freedom model and uses data obtained from experimental studies using an artificial mouth to test the model and improve its parameters. Linear stability analysis is used to study the threshold behaviour. Comparisons are made with threshold measurements and frequency responses of the artificial mouth, extending the work of Cullen [1].

1. INTRODUCTION

The behaviour of musical reeds has been the subject of much study since the pioneering work of Helmholtz [2]. Most reeds can be classified as one of two types:

- Inward Striking
- Outward Striking

Each type describes the response of the reed to a slow increase in supply (blowing) pressure. The inward striking reed responds by closing as the supply pressure is increased. This is exhibited, for example, by the oboe reed. The outward striking reed responds to an increase in blowing pressure with an increase in aperture. Helmholtz originally put brass players' lips into this category.

These reeds are then coupled to an acoustical resonator (the instrument). Self-sustained oscillation at threshold can only occur if the playing frequency and phase are in the correct configuration [3, 4]. For inward striking reeds this means that the playing frequency is below the acoustical resonance, and that the phase relationship is given by $\angle C(\omega) = +\pi/2$, where

$$\angle C(\omega) = \angle h(\omega) - \angle \Delta P(\omega), \tag{1}$$

h is oscillating component of the the lip opening, and $\Delta P = (p_m - p_i)$ is the oscillating pressure difference across the lips, as shown in figure .

For outward striking reeds, the opposite relationships are true. The playing frequency must be above the acoustical resonance, and the phase relationship is $\angle C(\omega) = -\pi/2$.

These conditions would imply that when playing any instrument whose reed fell into one of these categories, it would be impossible to "lip" that instrument to one given side of the resonance

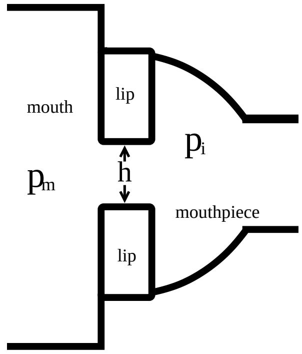

Figure 1: Diagram showing essential parameters of any lip model

frequency. However, this is not the case with brass instruments, where players can play above, below, and on the instrument resonance frequencies [5, 6]. This behaviour is impossible to reproduce using a single degree of freedom model of the lips [1, 7], but is easily reproducible using a two degree of freedom model [5, 6].

One such model is used in section 4, and we discuss the choice of model parameters based on experimental measurements, described in sections 2 and 3.

2. EXPERIMENTAL SETUP

The experimental work used in this paper is based on previous work by Cullen et al [7], Neal et al [5], and others. The artificial mouth used is shown in figure 2. This mouth differs from those from previous studies [1, 5] mainly by mounting the lips externally. This allows for easy adjustments of embouchure, as well as the freedom to use virtually any mouthpiece with the system. This mouth also has many quantifiable control parameters. The water pressure in the lips, the equilibrium opening between the lips and thickness of the lip channel can all be accurately and quantifiably controlled. Different materials can be used for the lips and their internal fluids.

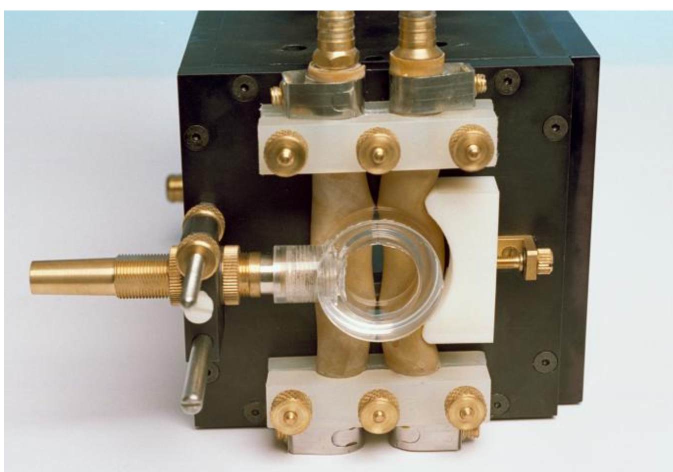

Figure 2: Photograph of the artificial mouth

A transparent mouthpiece was also used, as can be seen in figure 2. The design of this mouthpiece has been used by many other researchers in this area before, and using this mouthpiece instead of the standard type does not significantly affect the playing of the instrument. This has been verified with human players, whose only difficulty playing such a setup stems from holding the instrument in a different fashion. The use of a transparent mouthpiece allows both qualitative and quantitave measurements to be made of the lip motion using a normal musical instrument. Previous studies in this area have used a straight section of cylindrical tubing to imitate a trombone [5], but here we use a real instrument. The impedance curve of the trombone used, with the transparent mouthpiece attached and no slide extension, can be seen in figure 3.

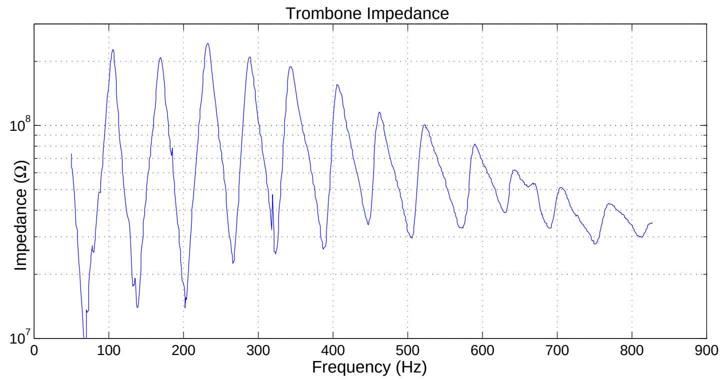

Figure 3: Impedance curve of the trombone, with transparent mouthpice attached

The artificial mouth was mounted on an optical rail, together with a trombone, laser, photodiode and microphone, as shown in figure 4. Note that the perpendicular mounting of the trombone is a result of using the transparent mouthpiece and does not affect the performance of the system in any significant way.

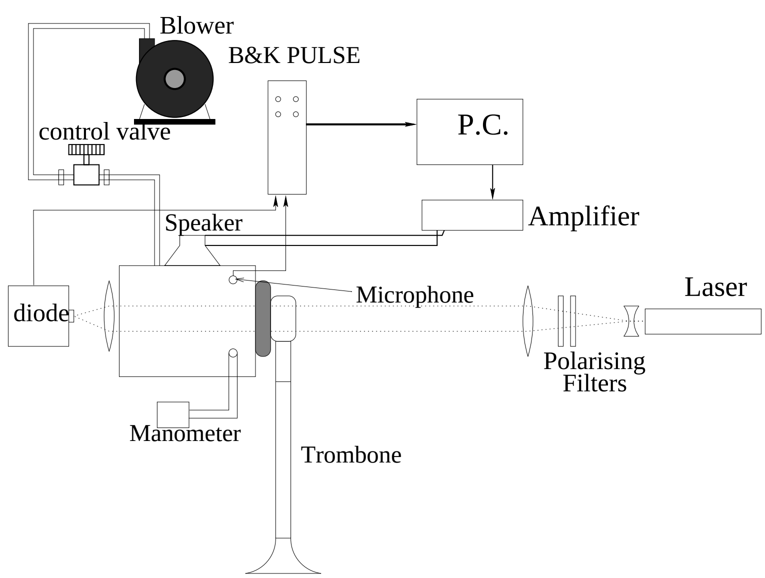

Figure 4: Diagram of Experimental Setup

Data was recorded using a Brüel and Kjær PULSE system. This system is capable of performing real-time cross-spectrum frequency analysis. This is used to measure the response of the lips to a given oscillating input pressure, provided by the loudspeaker. There are several methods one can use to excite the lips, the most useful in this situation being the “chirp” method, where a short, swept sine wave is input into the mouth cavity. The amplitude of the lip response is measured by the photodiode, and the input pressure is measured by a Brüel and Kjær $\frac{1}{4}$” microphone. The PULSE system calculates the response (the photodiode signal $\hat{h}(\omega)$) of the lips to the oscillating input pressure $\hat{p}_m(\omega)$ as measured by the microphone. The frequency response is given by equation 2 [8]:

$$G(k) = \frac{\overline{\hat{h}^*(k)\hat{h}(k)}}{\overline{\hat{h}^*(k)\hat{p}_m(k)}} \tag{2}$$

The number of measurements used in taking the averages is defined by the user. A typical lip frequency response measurement is shown in figure 5.

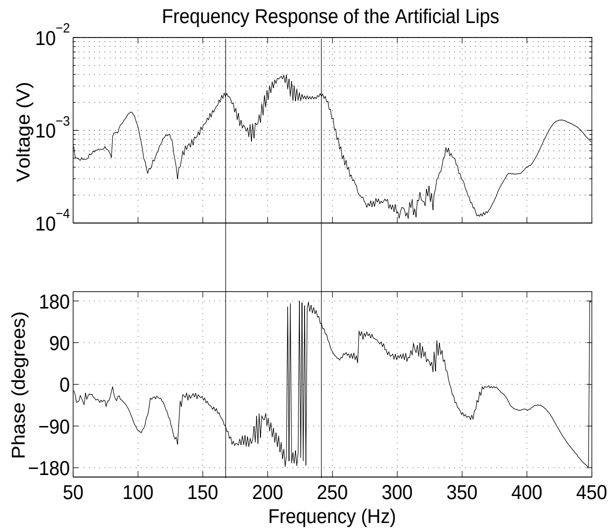

Figure 5: Frequency Response of a typical configuration. The vertical lines show the destabilising outward and inward striking resonances, at 167Hz and 242Hz respectively.

3. EXPERIMENTAL RESULTS

Figure 5 can be used to identify not only the resonant modes of the lips, but also their category of motion (inward or outward). The phase of the lip response relative to the mouth pressure tells us which reed type a particular resonance is. As can be seen in figure 5, there are a number of resonances. The two solid vertical lines indicate the two most significant resonances. The low frequency resonance corresponds to an outward striking motion ($\angle C = -\pi/2$), and the higher frequency resonance corresponds to an inward striking reed ($\angle C = +\pi/2$). This corresponds to the work of Cullen [1] and Neal et al [5]. The transition between inward and outward regimes has been shown by Neal et al [6]. To demonstrate the phenomenon, measurements of threshold playing frequency as a function of tube length were taken, see figure 6.

These two sets of data now contain enough information to begin setting the parameters for a model of the lips around threshold conditions.

4. LIP MODEL

The lip model used here is a mathematically straightforward model, whose equations of motion describe the behaviour of a generic two-mode coupled oscillator, based on the model used by Cullen [1]. This is a highly linearised model, suitable only for analysis at threshold behaviour. Not only have the equations been linearised, but there is no provision here for lip collisions, closure, or other high-amplitude behaviour. The equations of motion for the model are:

$$\frac{d^2x_i}{dt^2} + \frac{\omega_i}{Q_i}\frac{dx_i}{dt} + \frac{1}{\mu_i}\frac{d\psi}{dt} + \omega_i^2(1+C_i)(x_i - x_i(0)) - C_i\omega_i^2(x_j - x_j(0)) = \frac{\left(p_m - \rho\overline{V_l}^2/2\right)}{\mu_i} \quad (3)$$

$$\frac{d^2\psi}{dt^2} + \left(\frac{\omega_a}{Q_a} + \frac{Z_a\omega_a}{Q_a}\frac{b\overline{H}}{\rho\overline{V_l}}\right)\frac{d\psi}{dt} + \omega_a^2\psi - \frac{Z_a\omega_a}{Q_a}b\overline{V_l}(x_i + x_j) = 0 \quad (4)$$

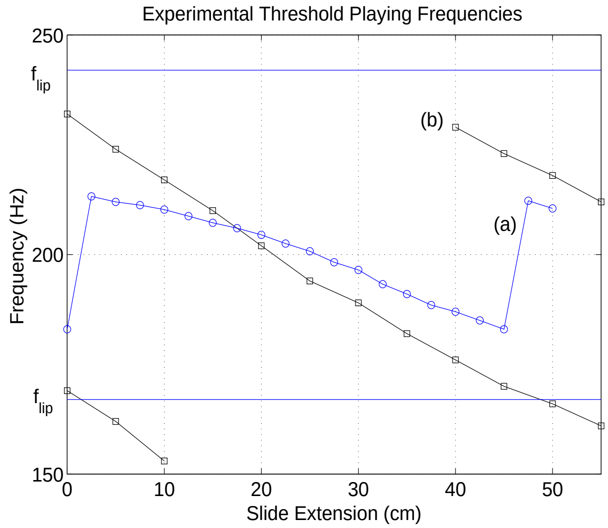

Figure 6: Experimentally measured threshold behaviour. Line (a) shows the threshold playing frequency. Lines (b) show the instrument resonances. The horizontal lines show the relevant lip resonance requencies, identified in figure 5

From the experimental data given in section 3 we can derive the initial control parameters for the model. First, the resonance frequencies of the two relevant lip modes can be established from figure 5, giving values of 167Hz and 242Hz . Secondly, the quality factors can also be estimated from this graph as approximately 6 and 4. These values are obtained from a visual examination of the graph, but more accurate measurements can, in principle, be obtained using curve fitting techniques [1]. However, as can be seen from figure 5, the resonances are more complex than a simple two-resonance model would reproduce. We can also experimentally obtain other values for the model, namely $b\overline{H}, \mu_i$ and l. However, because this model is heavily linearised these parameters may not relate quantitavely to the experimental readings. A more appropriate method of estimating these parameters is through iterative simulations - for which linear stability analysis is an ideal tool. We can attempt to fit the results from linear stability analysis to the results shown in figure 6. Fitting the model parameters to this data can give a good insight into how these parameters affect the behaviour of the model, as well as giving an indication of their complex relationships.

With appropriate parameters, the model exhibits threshold behaviour as shown in figure 7. The parameters used were as follows:

$$\omega_1 = 26.6rad/s, \quad \omega_2 = 38.5rad/s, \quad Q_1 = 3.7, \quad Q_2 = 3.6, \quad b = 7mm,$$

$$1/\mu_1 = 0.19m^2kg^{-1}, \quad 1/\mu_2 = -0.19m^2kg^{-1}, \quad x_1(0) = x_2(0) = 0.5mm, \quad C_1 = C_2 = 0$$

Of these, only the resonance frequencies were taken directly from experimental measurements. All other parameters were estimated from experimental measurements to give a first order approximation. The simulations resulting from these initial parameters typically produce threshold behaviour quite different from the experimental case. For instance, the playing frequency could cross the resonance frequency curve at a different point, or not at all. To further refine these numbers, one can also consider the blowing pressure. The magnitude of the μ_i parameters controls the amplitude of the threshold mouth pressure. Again, the experimentally measured values of μ_i will often produce unrealistic results, requiring that they be altered to reproduce the experimental behaviour more accurately.

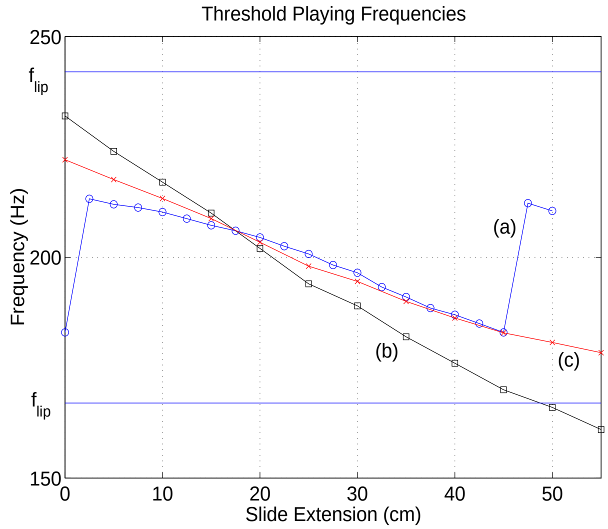

Figure 7: Threshold behaviour of the model. Lines (a) and (b) are the same as those shown in figure 6. Line (c) shows the simulated threshold playing frequencies, as obtained from linear stability analysis.

5. CONCLUSIONS

Using measurements of physical properties of lips can give first order indications for model parameters. However, choosing the effective parameters of a lip model needs to be handled carefully, due to the fact that the lip model is a simplified version of the real situation. Lip resonance frequencies can be obtained from experimental mechanical response measurements, but other parameters should be finalised on a reverse-engineering basis. Nevertheless, the effectiveness of a two dimensional model in reproducing the “lipping” style behaviour observed experimentally is clear.

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