Mechanical response measurements of real and artificial brass player's lips.

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Abstract: Mechanical frequency responses of human and artificial lips in brass instrument playing have been measured using a high-speed digital video technique, in an attempt to classify the true nature of the "lip-reed." Four semiprofessional human players were used, and three notes played on a trombone were studied. All measurements revealed a strong mechanical resonance with "outward striking" behavior; the played note always sounded above this frequency. Several measurements also showed a weaker second resonance, above the played frequency, with "inward striking" behavior. The Q values of the dominant resonances in human lips were lower than those typical of artificial lips.

PACS numbers: 43.75.Fg, 43.75.Yy [TR]
Date Received: July 18, 2007 **Date Accepted:** October 9, 2007

1. Introduction

Brass instruments produce sound as a result of self-sustained oscillations of the player's lips. The lips are destabilized by application of an overpressure from the lungs, causing a pressure difference to be established between the mouth cavity and the mouthpiece. A complex nonlinear coupling between the resulting airflow, the lips themselves and the resonances of the instrument air column allows self-sustained oscillation and the production of a musical note.

The mechanical properties of the lips are important in determining the playing frequency of a note.[1] A player must adjust the tension and mass distribution of the lip tissue in order to tune any mechanical resonances so that they may usefully interact with the instrument (see, for example Refs. 2–6). Up to now a full description of real human lips has proven difficult, and computational models have relied on parameters obtained from experiments with artificial lips, such as the pioneering work of Cullen *et al.*[7] The principal aim of the present study was to measure the mechanical properties of human lips when formed into playable embouchures.

Several computational models of the lip-reed have been suggested. A lumped element model with one degree of freedom presents the simplest description. Each lip is condensed into a single mass attached to a solid boundary by a spring-damper system. The lips move symmetrically, so only one degree of mechanical freedom is required. This model already describes an impressive array of brass instrument behavior. It fails, however, to reproduce an important feature of human players: the ability to "lip" a note above and below the relevant acoustical resonance frequency of the air column of the instrument.

This problem can be resolved by ascribing two degrees of mechanical freedom to the lips,[4,8,9] in a manner similar to that which has been used to model the human vocal folds.[10,11] Experiments using artificial lips[12] in combination with computational modeling have shown that an "outward-inward striking" resonance pair, in the terminology of classical reed physics,[1] can provide the necessary flexibility. The terms outward striking and inward striking here refer to the manner in which the aperture of a musical reed is expected to respond to a steady increase in supply pressure. The aperture of an outward striking, or "blown open,"[3] reed tends to widen as the supply pressure is increased. Conversely, the inward striking, or "blown closed," reed tends to close. However, no direct measurements have yet provided convincing verification of outward-inward resonance pairs in the lips of human players.

The conventional light transmission method of measuring the mechanical response of artificial lips, described in Sec. 2.1, involves measurement of the modulation of a laser beam passing between the lips. Since this technique could not be used with human players, an alternative technique using a high speed digital video camera was evolved; this is described in Sec. 2.2. The new technique was first validated by comparing mechanical response measurements performed on artificial lips using both the video method and the conventional transmission method. This validation is described in Sec. 3.1. Finally the video method was applied to human subjects in an attempt to classify unambiguously the phase behavior of the human lip-reed. The results of this experiment are presented in Sec. 3.2.

2. Experimental Methods

In the first part of this study a set of artificial lips was used to play a tenor trombone in the first position. The setup was based on one previously documented.[7] The lips were formed from water-filled latex tubes of 20 mm diameter. The principal control parameter was the internal water pressure, which was adjusted by varying the height of a water column. The lips were stretched across a circular aperture on the front face of a box representing the mouth cavity. A transparent mouthpiece[13] was coupled to the lips, which allowed for easy optical access to the lip opening. A compressed air source supplied an overpressure to this cavity, resulting in an air flow which destabilized the lips and generated a musical note.

2.1 Transmission method for measuring mechanical response of artificial lips

The mechanical response of the artificial lips was first measured using a light transmission method, which is a development of the photoelectric method of Backus.[14] This technique has been described previously[7] and has been widely used for experiments with musical valves.[10,15]

An expanded laser beam was directed through the opening between a pair of artificial lips. The beam was then focused on to a photosensitive diode. Oscillation of the lips caused a modulation in the intensity of the beam which was measured by the diode. With a suitable calibration procedure this led directly to a time domain signal representing the oscillating lip opening. The lips were acoustically driven with a sine wave chirp (typically of 10 s duration) from a loudspeaker coupled to the "mouth" cavity behind the lips. The chirp signal amplitude was calibrated so as to maximize the signal-to-noise ratio of the measurements. The acoustic pressure in the cavity was recorded with a Brüel & Kjær type 4192 microphone. It was assumed that the force acting on the lips was proportional to this signal. All signals were generated and recorded using the Brüel & Kjær PULSE system. This allowed a direct calculation of the frequency response function of the lip opening, defined as

$$H(f) = \frac{\overline{G_{hp}(f)}}{\overline{G_{hh}(f)}} \tag{1}$$

and derived from the averaged power spectrum of the lip motion $\overline{G_{hh}(f)}$, and the averaged cross spectrum of the lip motion with the mouthpiece pressure $\overline{G_{hp}(f)}$. The averaging process permitted several repetitions of the excitation sweep in order to further increase the signal-to-noise ratio of the measurement.

2.2 Video method for measuring mechanical response of artificial and human lips

The optical arrangement required for the transmission method made it impossible to use with human players. A new setup was developed whereby the motion of the lips was recorded directly to digital video using a high-speed camera. This type of camera has been extensively applied to the study of lip reeds in self-sustained oscillation.[12,13] The application to the low amplitude oscillations induced by a mechanical response measurement presented a particular experimental challenge. A primary objective of this study was thus to verify that the new method could consistently reproduce the response curves obtained with the established method. An attempt to measure the mechanical properties of human vocal folds[16] successfully used a similar approach. However, the induced vibrations were driven from a mechanical shaker and not from an acoustical signal. The vocal folds in this study were also relaxed, and not held under tension as for a lip reed embouchure. This was an important issue for the present work: as the lip tension was increased the amplitude response for the same level of loudspeaker driving decreased. Thus it was important to carefully monitor the high speed camera signal to ensure that a sufficiently good signal-to-noise ratio could be obtained.

To implement the video method, the optics (laser, lenses, diode) from the previous setup were replaced with a high speed digital camera (Vision Research Inc., Phantom v4.1) and a high intensity light source (Schott KL1500 LCD). The camera was oriented to capture the same open area region as with the transmission method. The artificial lips were again driven by a calibrated sine sweep. Each frame from the video was analyzed to deduce the instantaneous lip opening. Concatenation of this information provided a time domain signal describing the oscillating lip opening, directly analogous to that produced by the diode in the transmission method.

An important difference between the two methods was the effective sample rate: in the transmission method this was governed by the signal aquisition system (typically 60 kHz), while for the video method it was limited by the frame rate of the camera (typically 2 kHz at a resolution of 128×256 pixels). This reduced the upper frequency range of the measurements, but this was not a significant problem as the relevant frequency range of the important lip resonances was typically 80–200 Hz. The microphone signal was digitally sampled using the Brüel & Kjær PULSE system, together with a trigger signal that allowed synchronization of the camera video with the pressure recording.

Only a single repetition of the excitation signal could be used. The sweep was generally of shorter duration (around 4 s) than with the laser-diode setup, which further limited the signal-to-noise ratio of the measurements. Despite these apparent shortfalls, the new system was able to faithfully reproduce the artificial lip response curves measured with the transmission method, as will be shown in Sec. 3.1.

To adapt the video method for use on human players, a special double-shanked mouthpiece was constructed. In the normal playing configuration the mouthpiece coupled the player to the trombone via the right-hand shank, with the left-hand shank remaining closed. Upon depression of a control valve the right-hand shank was closed off and the left-hand shank opened, coupling the player to a cavity driven by the loudspeaker. This allowed the player to form an embouchure designed to play a specific note, before subjecting the embouchure to forcing by the calibrated sine sweep. The arrangement is shown schematically in Fig. 1.

3. Results

3.1 Comparison of mechanical response curves of artificial lips obtained using the transmission and video methods

Figure 2 shows three typical mechanical response curves of the artificial lips obtained with the transmission method. The plot illustrates the importance of the principal control parameter for the lips: the internal water pressure. As the internal pressure is increased the resonances of the lips are seen to increase in frequency. This can be associated with an increase in the effective stiffness of the lips: the latex tubing is stretched tighter by the increase in water volume.

Clearly evident from Fig. 2 is the presence of a pair of resonances, between which lies the playing frequency. For example, in the low water pressure curve the first resonance lies at 136 Hz, and the second at 184 Hz. The playing frequency was 174 Hz, close to F2. The lower resonance always shows an outward striking ($-90°$) phase behavior, in the terminology of classical reed physics.[1,17] The upper resonance shows an inward striking ($+90°$) behavior. The con-

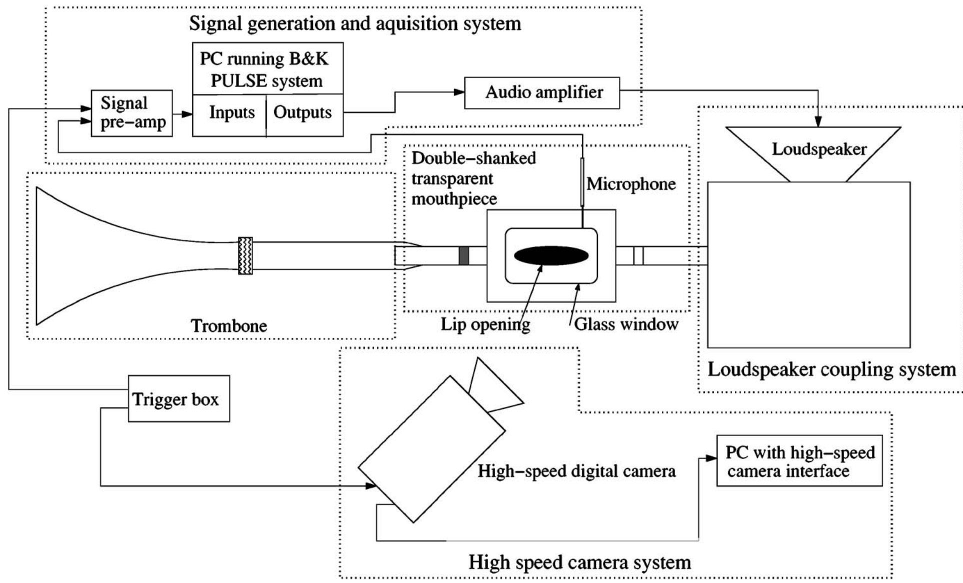

Fig. 1. The setup for mechanical response measurements on human lips using the video method.

sistent appearance of two resonances in such curves has led to the suggestion that a model incorporating at least two degrees of freedom should be required to simulate computationally realistic oscillations of the lip reed.[7,8,12]

Mechanical response measurements using both the transmission method and the video method are shown together in Fig. 3. A satisfactory feature of this plot is the close agreement between the curves in both magnitude and phase. In particular, the resonance frequencies and the phase angles at these frequencies match to within 5%. This is close to the tolerance between consecutive measurements with the transmission method, leading to the conclusion that the video method appears to be reliable.

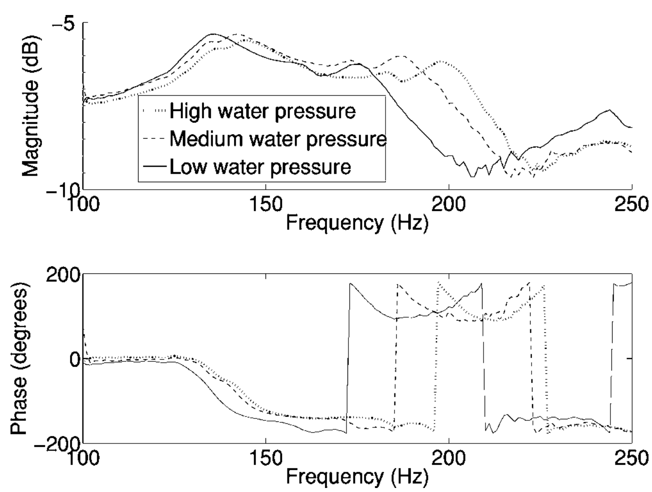

Fig. 2. A plot of three mechanical response curves for different artificial lip embouchures, obtained using the transmission method.

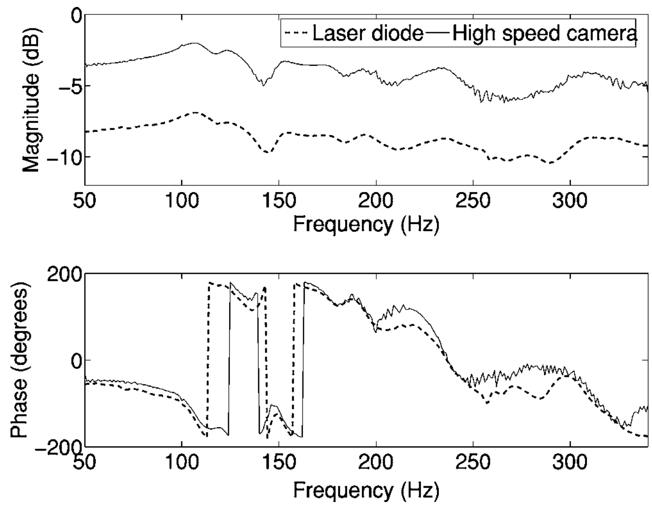

Fig. 3. A comparison between the transmission and video methods for measurement of the mechanical response of the artificial lips. The magnitude curves have been offset by 5 dB for display purposes.

3.2 Mechanical response properties of human lips

A selection of mechanical response curves obtained using human lips is presented in Fig. 4. The embouchures studied corresponded to three played notes: $B_1^\flat$ (the pedal note), $B_2^\flat$ and F_3. These represent the lower range of playable notes on the tenor trombone.

All curves reveal one dominant resonance. This resonance consistently lies below the frequency of the played note, which together with its −90° phase behavior leads to the suggestion that it acts like the outward striking reed of Helmholtz.[17] In the case of the $B_1^\flat$ pedal note shown in the figure this resonance was at 32 Hz, identified from the −90° phase crossing. The played frequency was 58 Hz.

An interesting feature of the curves shown here is the nature of the phase response above the frequency of the played note. After the first resonance it continues down through the inward striking reed angle at +90°. The magnitude curves at this frequency generally show a small peak, though for some measurements the peak disappears below the noise floor.

The progression of the phase response through the inward striking phase angle is generally smooth and consistent. This provides a strong indication that for this frequency, together

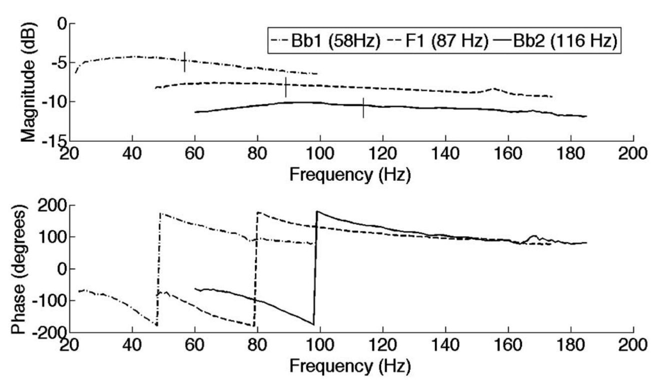

Fig. 4. A plot of three mechanical response curves obtained with human lips, using the video method. The played frequencies for each note are marked as vertical lines. The magnitude curves have been offset by 3 and 6 dB for display purposes.

with a suitable acoustical resonance, the embouchure would be able to accept a positive flow of energy from the flow through the lips and so sustain oscillations. For the $B_1^\flat$ pedal note this resonance was at 74 Hz, again identified from the appropriate phase crossing.

However, the presence of a particular mechanical resonance does not immediately reveal the frequency at which an embouchure will play. Rather, for a system containing two resonances the complex interaction with the acoustical modes of the air column means that a coupling between the two mechanical resonances can occur such that the played frequency will fall between them. In this study the playing frequencies of all the notes fell between the two resonances in the same manner as observed with artificial lips.

Previous studies on the transverse motion of the lips during playing have suggested that the lip surfaces follow an eliptical trajectory.[4,8,9] The results here could support such a motion, but could also be described by a simple two mass transverse model such as that frequently used for the human vocal folds.[10,11] The coupled nature of the resonances means that it is difficult to relate particular resonances to specific degrees of freedom.

A second interesting feature of the plots is the shape of the lip resonances. The peaks are of a significantly lower Q value as compared with those of the artificial lips. Typical Q values for the artificial lips[7] range from 8 to 10. In this study the lower outward striking resonances displayed Q values from 1.2 to 1.8. It is possible that the relative broadness of the resonances would make it easier for a human player to "lip" a note far away from the standing wave frequencies of the air column. This result could have implications for parameter choices in the computational modeling of the lip reed.

A recent study measured the mechanical impedance of artificial and human lips.[18] A shaker incorporating an impedance head was placed in contact with a single lip. The Q values of the dominant human lip resonance were lower than those of the artificial lip when filled with either water or glycerine. Interestingly the glycerine-filled artificial lip displayed typical Q values of 4–6 which were a closer match to those of the real lip, typically 1.4–1.6. This result appears to lie in close agreement with the current study.

The general difference in Q values between real and artificial lips is likely to be due to differences in the internal damping of the lips. The artificial lips consist of water surrounded by latex, whereas human lip tissue is constructed from a lattice of skin and muscle cells containing water. One study[19] has deduced some relevant mechanical parameters for human lips and the results here appear to be in broad agreement.

4. Conclusions

This paper has demonstrated the feasibility of measuring the mechanical response properties of human lips formed into playable embouchures. Since the conventional experimental techniques used for artificial lips could not be directly transferred to human players, a video method involving the use of a high speed digital camera was developed and validated.

Application of the video method to human lips has shown that at least two mechanical resonances may be significant in the interaction between the lips and the instrument air column. The magnitude curves suggest that for the range of notes studied the lower resonance is dominant. However, it has been shown elsewhere that a second, apparently weaker resonance can play an important role in the destabilization of an artificial lip embouchure.[12]

The two resonances that are frequently observed appear to have the appropriate phase behavior for a useful reed destabilization, in a manner similar to outward-inward striking resonance pairs frequently observed with artificial lips.

The Q values of the human lip resonances were typically 10–20% of those seen with the artificial lips. This result is in broad agreement with a recent study on the mechanical impedance of human and artificial lips.

Acknowledgments

This work was funded by a Ph.D. grant from the EPSRC, UK. The authors wish to thank A. Downie and D. Low for technical assistance in the construction of the setups, and the four trombone players who kindly volunteered their time and lips.

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