BASIC TESTS FOR MODELS OF THE LIP REED

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Abstract

Simple lip reed models treat the brass player's upper lip as a single mass that moves with one or two degrees of freedom. Helmholtz's outward-swinging door model operates at a playing frequency that is higher than both the lip frequency and the relevant air column resonance frequency. A simple empirical test with an isolated mouthpiece shows a very different behavior and favors either the sliding door or a two-dimensional hybrid model. One can easily play the mouthpiece well below its resonance or "popping" frequency, but not above it. A similar behavior is observed in "bending" notes on the first few usable resonances of the complete instrument.

An operational definition for the lip frequency includes both the mechanical influence of the mouthpiece rim and acoustic feedback from the cup and throat, which act as a Helmholtz resonator. When the mouthpiece is attached to the complete instrument, an open shunt hole in the backbore provides an *ad hoc* approximation to that frequency. The playing frequency is measured just after closure, before the embouchure can be modified. A plot of playing frequency versus lip frequency shows good agreement with the hybrid model's behavior at low frequencies. No simple model gives the correct behavior for higher playing frequencies, which drift above the resonance frequency but remain below the lip frequency.

Stroboscopic observations reveal a wave disturbance in the mucosa of the upper lip, much like that on the surface of water but turned upside down. Within the narrow passageway between the lips, the air stream drives the mucosal wave, which in turn acts as a valve for the volume velocity injected into the mouthpiece. More realistic models should result from using several masses and taking advantage of existing results for the similar behavior of the vocal folds.

INTRODUCTION

The question of how the lip reed driver for a brass instrument actually operates is a long-standing problem that has yet to receive a definitive answer. What is the correct description of its motion? How does that motion modulate the volume velocity injected into the mouthpiece, and how is it influenced by acoustic feedback from the instrument's air column? An extensive list of references on this topic is included in a recent article by Cullen, Gilbert and Campbell [1].

Currently three simple lip reed models are under consideration. According to Helmholtz's outward-swinging door model, the lips are blown open by a positive pressure difference between the mouth and the cup of the mouthpiece. A sliding door model has the lips being pulled together by a drop in pressure in the air stream passing between them (Bernoulli's principle). Computer simulations in the time domain carried out by Adachi and Sato have confirmed earlier theoretical results for these models [2]. Those authors have also introduced a two-dimensional hybrid model that incorporates both driving forces by allowing orbital motion [3].

Attempts to relate experimental results to these models, especially the two older ones, tend to be quite confusing. The lips are interpreted as acting sometimes like one model and sometimes like another, and often we are left with new mysteries rather than answers. This paper presents some very simple experiments, which are actually little more than careful observations, as a contribution toward clearing up that confusion.

SIMPLE EMPIRICAL TESTS

The outward-swinging door behaves differently from the other simple models in that its playing frequency is higher than that of the relevant peak in the air column's input impedance. The ability of a brass player to "bend" or drop the playing frequency smoothly and continuously to well below the second or third resonance frequency of the instrument provides clear evidence that this is not a valid model for the real lip reed. Attempts to push a note sharp from an input impedance peak have little effect, and trying too hard causes it to jump up to the next peak.

Chen and Weinreich investigated the behavior of the lip reed while it was driving a Helmholtz resonator [4]. With only one impedance peak, there could be no regime of oscillation. A simplified version of that experiment can be performed by playing on an isolated mouthpiece. Figure 1 shows waterfall plots of acoustic spectra in the mouthpiece as the lips are buzzed into (a) a trombone mouthpiece, (b) a trombone mouthpiece adapted to use a trumpet rim, and (c) a trumpet mouthpiece. Time increases from front to back, with each plot showing a continuous glide upward, then one that drops in pitch, and finally the lowest frequencies for that rim size. The broken curve superimposed on each plot shows the spectrum of the brief "pop" from slapping the rim against the palm of one's hand.

The inside diameter of the mouthpiece rim has a significant influence on the behavior of the lip reed. The small rim size of a trumpet or French horn mouthpiece makes it easier to buzz the lips at higher frequencies and imposes a vague low frequency limit, with or without the rest of the mouthpiece. The large rim diameter suitable for a trombone facilitates reaching lower frequencies, as can be seen by comparing the top portions of plots (a) and (b) in Fig. 1. However it also requires more "muscling" of the embouchure to play higher frequencies, comparable to the condition of buzzing into open air without the aid of a rim.

The most striking feature in these three plots is the sharp cutoff in response of the lips very close to the input impedance peak. Some hysteresis effects are visible here, with the upward glide ending slightly higher than the frequency at which the lips start to respond in the downward glide. The spectrum analyzer used to generate these plots is convenient but hardly necessary for conducting this simple test; Helmholtz could have done it by ear. The brief "pop" produced by a hand slap on the rim lasts long enough to hear the pitch of the impedance peak, particularly for the larger mouthpieces.

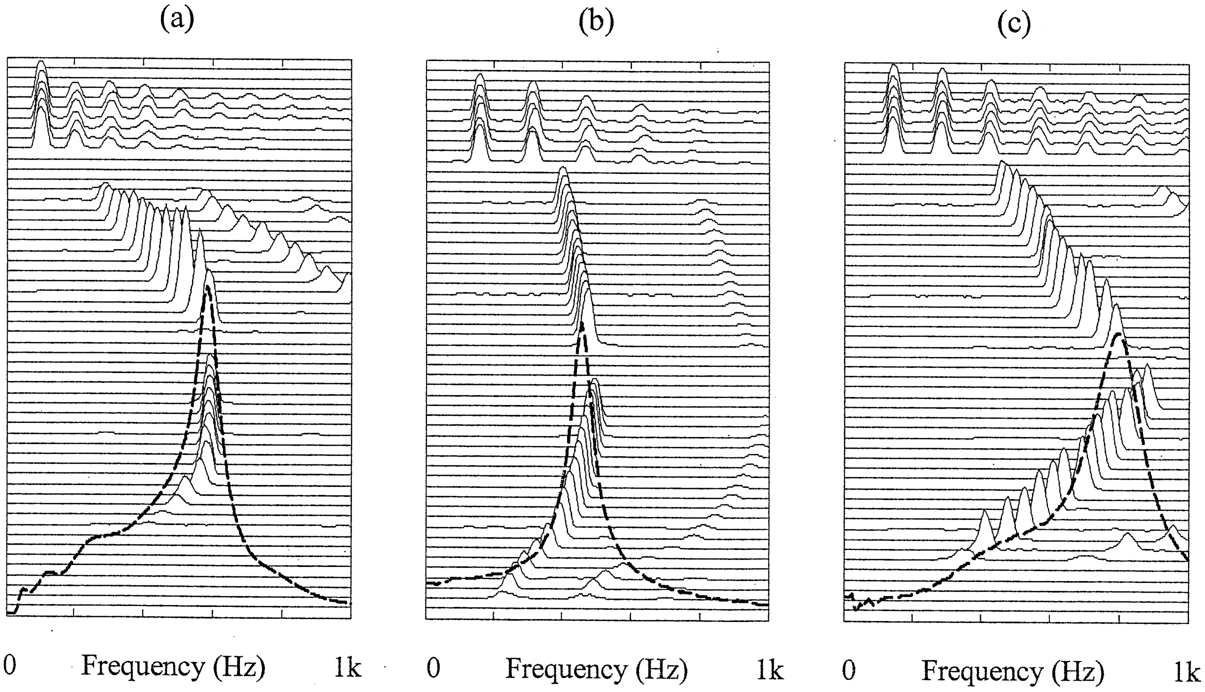

Figure 1. Waterfall spectra (time increasing front to back): upward glide, downward glide, then lowest pitches for rim size. Broken curve: spectrum from "popping" the mouthpiece rim by hand. a) Trombone mouthpiece; (b) trombone mouthpiece with trumpet rim; (c) trumpet mouthpiece.

EXPERIMENT WITH A SHUNTED MOUTHPIECE

The simple tests of the previous section rule out the outward-swinging door model, but they do not distinguish between the sliding-door and hybrid models, both of which operate below the relevant resonance frequency. In order to compare those models with real lips we must have a means of measuring a "lip frequency." Unlike the mass and spring combinations of the simple models, a real upper lip cannot be plucked and allowed to perform damped oscillations. (The implausibility of a lip moving as a lumped element at even a few hundred hertz provides a good clue about its real motion.)

The influences of the mouthpiece rim and acoustic feedback from the cup and throat are always present, and they are essentially immediate compared to that of the delayed reflections in the air column of the complete instrument. This suggests that an operational definition for the lip frequency should include those unchanging influences but not the resonance effects arising in the rest of the air column. A simple *ad hoc* approximation to that condition is achieved by opening a shunt hole (6.35 mm diameter, in a short chimney) in the backbore of the mouthpiece. Figure 2 shows the input impedance curves for a complete trumpet with the shunt hole closed (solid) and with it open (broken). Failure to close off the rest of the air column when the hole is open gives rise to the notches seen in the broken curve. These do not interfere with playing an arbitrary frequency except near the main peak, which is shifted to the right under playing conditions by lip intrusion into the cup.

The performer first stabilizes the frequency close to a desired value with the hole open. Then the hole is closed without interrupting the sound and the playing frequency for the complete instrument is captured very quickly, so that the embouchure is still set for the open hole lip frequency. In Fig. 3 the results of this experiment are compared with computational results for the outward-swinging and sliding door models, which were obtained in time domain simulations by Adachi and Sato [2]. Horizontal lines show the resonance frequencies: dashed = experimental values; dotted = those of Adachi and Sato. There is clear disagreement between the Helmholtz model and the experimental results in the relationship of the playing frequency to both the lip frequency and the resonance frequencies. The sliding door model agrees well with the experimental results for the second resonance (the first one used on the trumpet), but above that the two behaviors differ noticeably.

The same experimental results are also shown in Fig. 4, with computational results for the two-dimensional hybrid model of Adachi and Sato [3]. Both frequency scales have been expanded and the entire plot has been broken into two parts to show the close agreement of the two behaviors, especially for the second and third resonances. The discrepancies in the lip frequencies at which the playing frequency shifts up to the neighborhood of the next resonance seem to indicate that feedback from the air column has a stronger influence on the actual lip reed than on this model, especially at higher frequencies. Small adjustments in the model's parameters may reduce that disagreement.

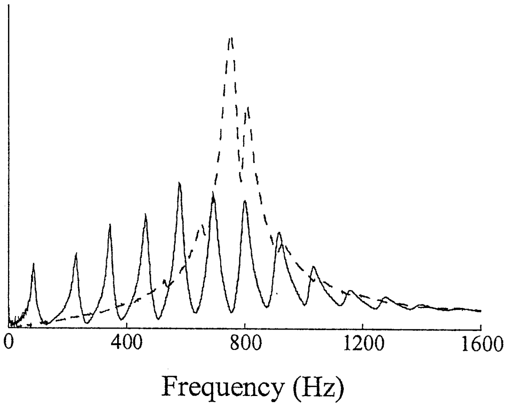

Figure 2. Trumpet input impedance curves. Solid: normal (shunt hole closed). Broken: shunt hole open.

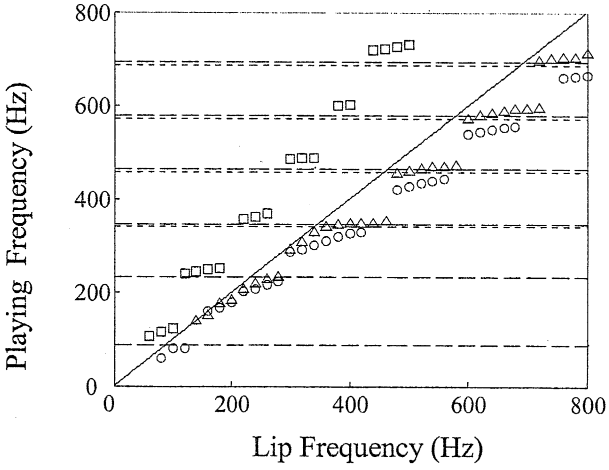

Figure 3. Playing frequency vs. lip frequency: □ = swinging door model; ○ = sliding door model; Δ = this experiment.

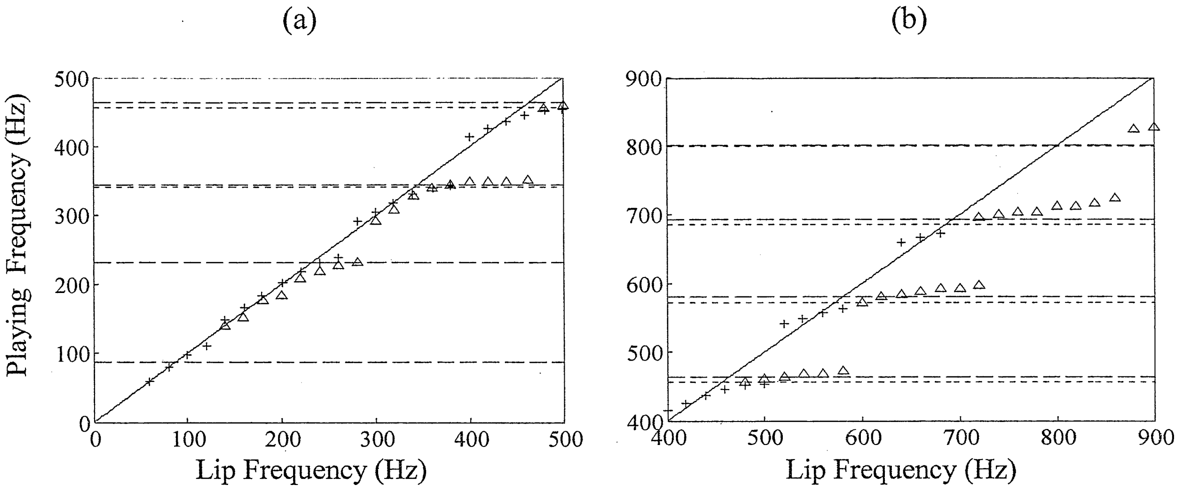

Figure 4. Playing frequency vs. lip frequency: + = hybrid model of Adachi and Sato, Δ = this experiment. Diagonal line: playing frequency equals lip frequency. Horizontal lines: dashed = experimental resonance frequencies; dotted = Adachi and Sato's. (a) 0 – 500 Hz; (b) 400 – 900 Hz.

DIRECT OBSERVATIONS OF LIP MOTION

It is unlikely that any simple modifications of the hybrid model will make it operate like the real lip reed at higher frequencies. The tendency of the actual playing frequency to become higher than the resonance frequency is a real behavior. The effects of lip intrusion into the mouthpiece cup are too small to make up the difference.

Progress toward a better model of the lip reed appears to require the use of at least two masses that can move out of phase with each other, as in early models of the vocal folds. Stroboscopic examination of the upper lip reveals a heavily damped, strongly driven wave disturbance with two antinodal regions in the narrow air channel between the lips. The motion of each particle is orbital, as in the hybrid model of Adachi and Sato. The ultimate model will probably have much in common with that for the mucosal wave on the vocal folds [5].

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