A stroboscopic study of lip vibrations in a trombone

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The purpose of the present study was to obtain detailed photographic sequences and lip motion data on which lip models for brass instruments may be more accurately based. The study expands upon an earlier study by Martin [J. Acoust. Soc. Am. **13**, 305–307 (1942)] by using advanced fiber-optic stroboscopy, a real instrument mouthpiece, and by studying two dynamic levels. The trombone was selected as representative of the brass family because its relatively large mouthpiece permitted the use of an optic probe. Lip motion was observed from the front and side for six notes (B♭2, F3, B♭3, D4, F4, A♭4) played at loud and soft dynamic levels. The video sequences were used to obtain information on lip opening area, lip motion perpendicular to airflow, and lip motion parallel to airflow. The data are tabulated and represented in graphic form. © *1996 Acoustical Society of America.*

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INTRODUCTION

More than 50 years ago, Martin investigated lip vibrations in a cornet mouthpiece using stroboscopic photography (Martin, 1942). The primary objective was to gain preliminary insight into the normal behavior of lips within the mouthpiece. Martin's study brought to light many crucial aspects of lip motion, including the relation of central lip opening to lip area, a confirmation that lip vibration amplitude decreases with frequency, and the general frequency content of lip vibrations. The study showed that motion takes place along the axis of air flow in addition to transverse motion. While this work was successful in its goal, it had two primary drawbacks: It did not use a real cornet mouthpiece, and it dealt only with a single dynamic level.

Several researchers have used Martin's findings as the basis for modeling trumpet excitation. For instance, Martin found that the lip opening varies nearly sinusoidally. Backus and Hundley (1971) used a sinusoidally driven mechanical lip model to demonstrate that such behavior could indeed generate harmonics due to the nonlinear nature of the flow. Dudley and Strong (1993) recently simulated this classic experiment on computer and obtained similar results.

Through experimental techniques, Yoshikawa (1995) addressed two traditional models of the lips. In one view, the lips are thought of as an outward striking reed (Helmholtz, 1877; Fletcher, 1979), or a "swinging door" opening in the direction of airflow. In the other, the lips are modeled by a "sliding door" oscillating transversely with respect to airflow (Saneyoshi *et al.*, 1987). Based on measured phase relationships between pressure and strain, Yoshikawa suggested that the outward striking reed model is most appropriate for low-frequency oscillations, and the transverse model best describes higher-frequency oscillations.

Based on Martin's (1942) published data, Strong and Dudley developed a model that considers both aspects of lip motion: transverse ("sliding door") and longitudinal ("swinging door") (Strong and Dudley, 1993). Their simulated results for lip opening show great similarity to Martin's results. Other researchers have relied upon Martin's data for guidance or validation of their lip models and/or experimental findings (Adachi and Sato, 1994, 1995; Dietz, 1988).

In short, the majority of research into the behavior of lips in brass instruments has used Martin's published photographs as a benchmark, or for confirmation of results. This fact alone underscores the importance of his work and the importance of actual photographic data. With the growing interest in physical modeling, it is probable that more researchers will rely on experimental data. In many cases, those investigating lip motion experimentally and/or theoretically have admitted to a lack of experimental data.

The purpose of this study was to obtain detailed photographic sequences and lip motion data on which lip models may be based. We expand upon Martin's investigation by using advanced fiber-optic stroboscopy, a real instrument mouthpiece and by studying two dynamic levels. The trombone was selected as representative of the lip reed family because its relatively large mouthpiece more easily facilitated the use of the optic probe.

I. DATA ACQUISITION

The principal piece of equipment used in this study was a rhino-laryngeal stroboscope (RLS model 9100), made by Kay Elemetrics. The stroboscope consists of a small fiber optic probe, a CCD digital camera, a digital enhancer, a computer, and a S-VHS video recorder. This device is normally used in clinical situations involving human vocal fold pathology. Using the principle of stroboscopy as applied to video, the apparatus is capable of capturing vocal fold oscillations in a "quasi-slow-motion" video sequence. Since lip vibration frequencies are similar to those of the vocal folds, this device was a natural choice for studying lip motion.

The trombone used in our study was a King Cleveland 605 student model tenor trombone with a Benge 12C mouthpiece. The instrument's tuning slide and playing slide were fully retracted throughout the study.

A 4-mm-diam hole was drilled into the mouthpiece as illustrated in Fig. 1 to view the lips from the front. Aligned slightly off axis, the hole was aimed at a point 5 mm inside

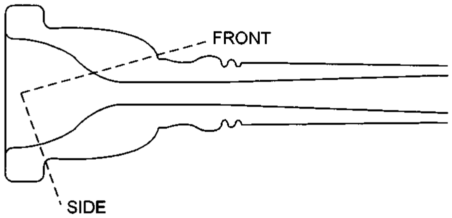

FIG. 1. Mouthpiece cutaway showing probe holes. Separate mouthpieces were used for viewing the lips from the front and from the side.

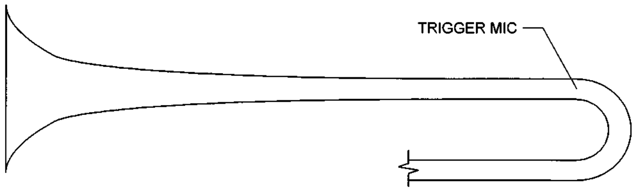

FIG. 2. Placement of trigger microphone within trombone bell. The fundamental frequency is very strong at this location and served well as a trigger signal for the stroboscope.

the mouthpiece along the central axis. A separate and identical mouthpiece was used for the side views. Aimed at the same point as above, the side view hole was also drilled at an angle in order to view the movement of the central portion of the upper lip.

A $\frac{1}{4}$-in. microphone was placed well inside the trombone bell to provide a trigger signal critical to the proper synchronization of the stroboscope (see Fig. 2). The stroboscope was set to capture one ''equivalent'' lip cycle every two-thirds of a second, corresponding to an effective phase advance of 18 deg per video frame. We say ''equivalent'' because the stroboscope exploits the principle of aliasing in order to capture the lip motion. This is accomplished by a computer-controlled stroboscopic light source with a strobing frequency based on the fundamental playing frequency. Many real cycles elapse during the capturing of one equivalent cycle. It is assumed that the lip vibrations are uniform throughout the real-time duration associated with each effective cycle. Furthermore, because the stroboscope requires the fundamental playing frequency to establish its strobe rate, only steady-state vibrations of the lips could be captured. No attempt was made to determine transient behavior.

An expert trombone player from the Music Faculty at Brigham Young University served as our subject. He was asked to play the following notes, all playable with the playing slide in first position (fully retracted): B♭2, F3, B♭3, D4, F4, and roughly A♭4, where C4 is middle C. Each note was played at two dynamic levels. The ''soft'' dynamic level roughly corresponded to *mezzo piano* (mp) and the ''loud'' level was considered *forte* (f). Throughout the study, a sound level meter monitored the playing levels. The mp and f dynamic levels were recorded approximately 1 m from the bell as 80 and 90 dB, respectively; the player regularly reproduced these levels within ±2 dB. Fundamental frequencies for each note were also recorded. With the exception of the last note in the series (A♭4, which is quite unstable), the player reproduced the notes within ±1 Hz.

The mouthpiece was rotated so that the probe was underneath the embouchure for the front views and to the player's right for the side views. Before inserting the optic probe, a warm, antifogging solution was applied to its lens to ensure clear pictures. The probe, being 4 mm in diameter, fit snugly into the holes and being wet from the solution, effectively sealed the mouthpiece cavity. In the opinion of the expert player, the probe was not overly intrusive and the instrument played much as it would under normal conditions.

II. DATA ANALYSIS

Each equivalent cycle consisted of 20 video frames. Zero phase value was assigned to the frame showing maximum lip closure. For the front view sequences, each frame was analyzed for three quantities of interest: central lip opening (hereafter called ''height''), the horizontal opening distance (hereafter referred to as ''width''), and the area defined by the lip opening (''area''). The side views were used to determine the trajectory of a central point on the upper lip.

In several instances, saliva obscured portions of the lips for one or two video frames. When this occurred at the center of the lips, the height was estimated based on the surrounding tissue. The width measurements represent straight-line distances from one side to the other and do not account for times when the orifice shape was bent. In some cases, especially during large amplitude vibrations, the upper teeth were visible. Their contribution to diminishing the opening area was neglected. Thus the area measurement was strictly the area of the opening defined by the lips.

All measurements were performed on computer in screen pixel units. Barrel distortion due to the wide-angle nature of the optic probe made calibration somewhat problematic. After correcting for view angle, a weighted average favoring the portion of the picture containing the lip opening was used to determine a linear calibration factor based on video frames of a millimeter grid. In this way, screen pixels were converted to centimeters.

Additional uncertainty was introduced in the determination of the actual lip boundaries. For width and height measurements, uncertainty existed at only two points. The boundary uncertainty was more severe for the area measurements since uncertainty exists all around the orifice. Several digital image enhancement and edge-detection processes were employed as aids, but the final determination of the lip boundaries was ultimately based on human judgement. For the front views, the data reported for each tone represent average values taken from seven separate effective cycles. The side view data, however, were taken from only one effective cycle. All factors considered, we believe the area values are precise to the nearest 1 mm^2 while the linear values are good to approximately 0.1 mm. Nevertheless, in cases where the opening and/or distances were very small, an additional half-digit is reported. Without doing so, there would be a significant quantization limit and the resultant curves would contain obvious discontinuities. In these cases, we are satisfied that an appeal to the physical situation, namely, an

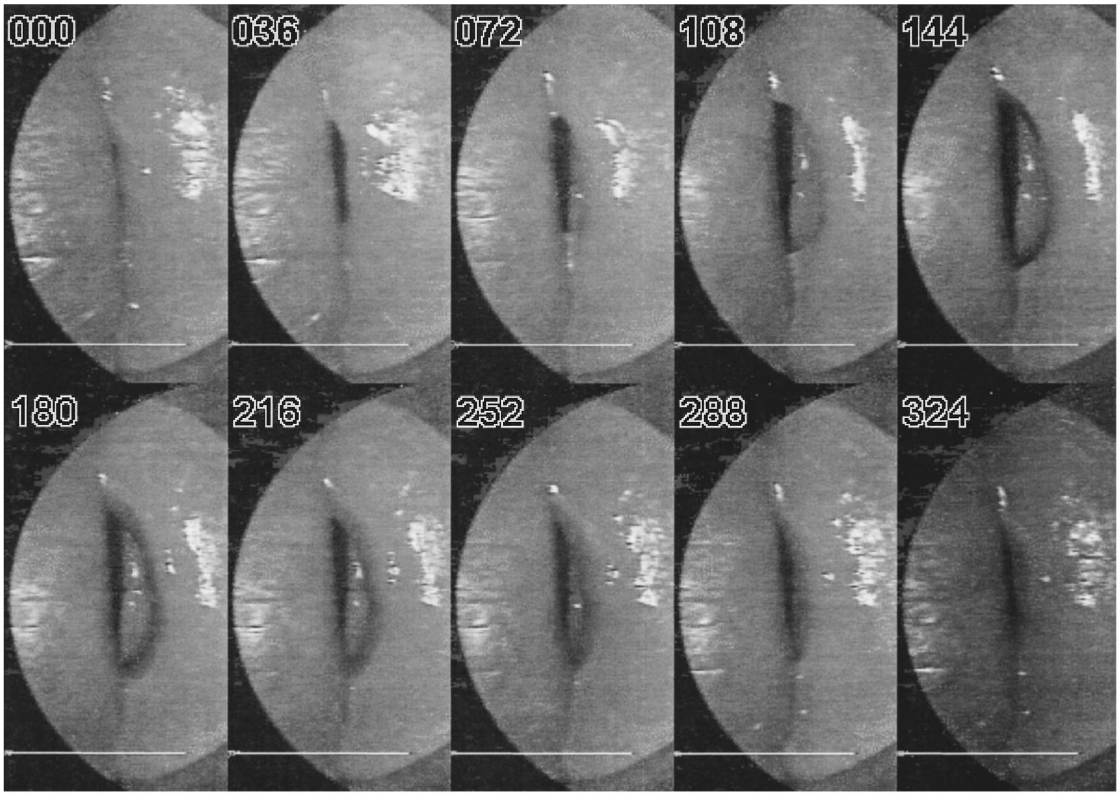

FIG. 3. Ten-frame sequence of B♭2 played *mezzo piano*. Successive frames are separated by 36 deg.

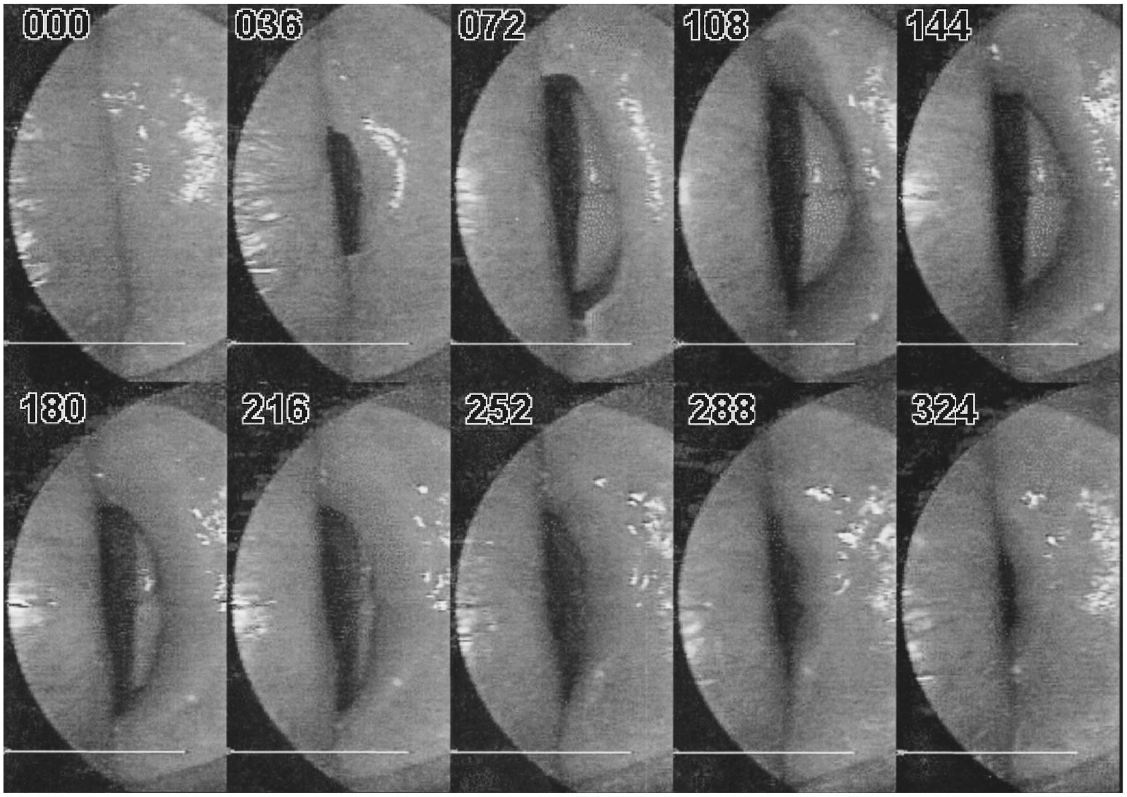

FIG. 4. Ten-frame sequence of B♭2 played *forte*.

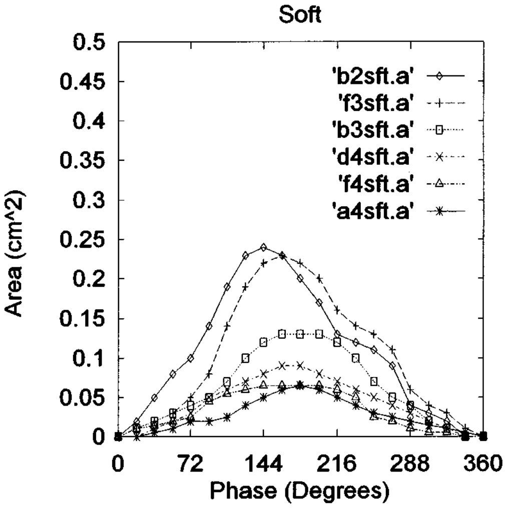

FIG. 5. Area functions for notes played *mezzo piano.*

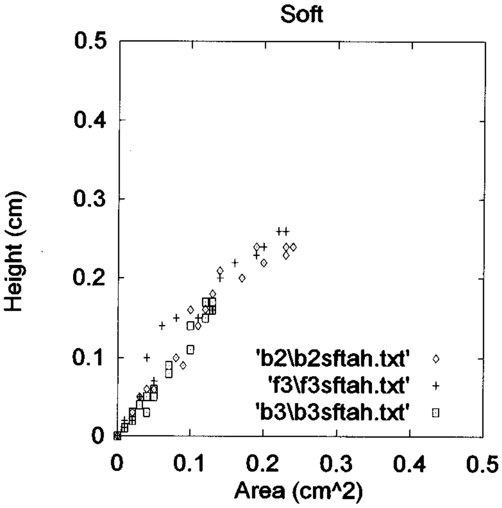

FIG. 7. Lip area versus height for B♭2, F3, and B♭3 played *mezzo piano.*

imposition of continuity, justifies this action, even though it is doubtful that level of precision was actually obtained.

III. LIP MOTION RESULTS

A. Font views

Figure 3 shows a 10-frame sequence for B♭2 played softly. Since each effective cycle contains 20 frames, this figure shows every other frame. (Due to particular software restrictions, a 20-frame sequence showing the complete lip opening cannot be displayed on the computer screen; each frame must be a separate screen image. To conserve and maximize screen space, a 10-frame sequence can be used if the region of interest is vertically aligned. The latter produces a useful and compact composite of an entire effective cycle.) Figure 4 shows the same note played loudly. From the figures, it is evident that the lips open more rapidly in the loud case than in the soft case.

Figure 5 compares the area functions for the six soft tones and Fig. 6 compares the area functions for the corresponding loud tones. Both plots were drawn to the same scale for ready comparison. The area functions for the soft tone exhibit a nearly symmetric behavior about the point of maximum opening. The lips clearly open rapidly and close gradually resulting in a more asymmetric area function for the loud tones. As frequency increases, the phase at which the maximum area occurs tends to increase generally, despite a few tones showing minor deviation from the trend. Martin (1942) reported similar findings in a cornet mouthpiece. As expected, and as also observed by Martin (1942), we see a general decrease in amplitude when higher notes are played.

Figure 7 shows comparisons of area versus height for the first three soft notes and Fig. 8 shows a similar comparison for the first three loud notes. There appears to be an almost linear relationship between area and height, supporting a variable rectangular model of the lips as a reasonable first approximation.

From the video sequences, it is apparent that the upper

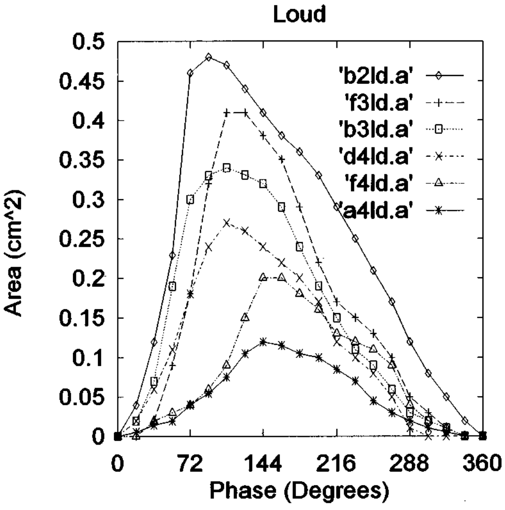

FIG. 6. Area functions for notes played *forte.*

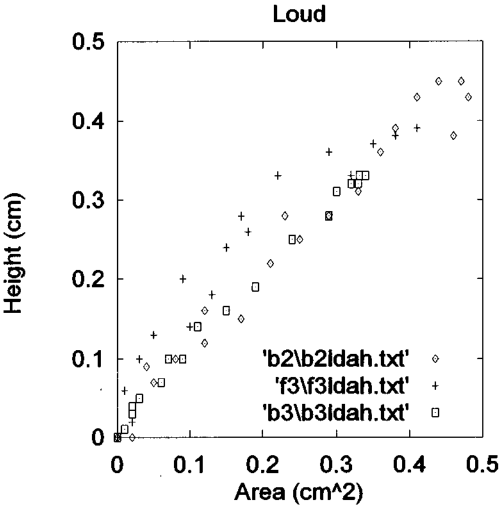

FIG. 8. Lip area and height for B♭2, F3, and B♭3 played *forte.*

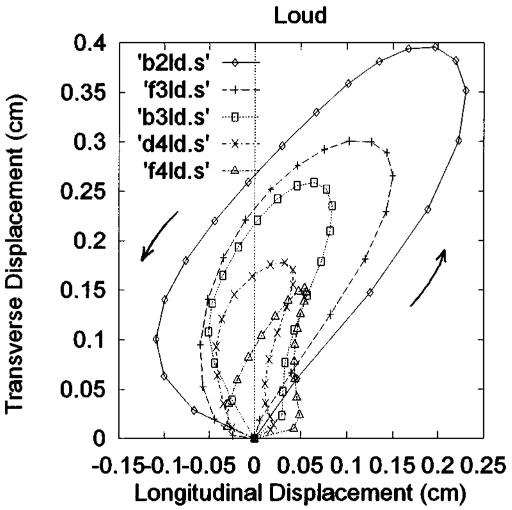

FIG. 9. Upper lip trajectories for first five notes played *forte*. The arrows show the direction of the trajectories through time. The origin represents the point of maximum lip closure. Longitudinal values increase in the direction of the mouthpiece.

lip vibrates considerably more than the lower lip for all cases—high and low frequencies, loud and soft dynamic levels. For loud, low-frequency tones, the edge of the upper lip appears to curl up as the lip begins its descent. This effect is much more noticeable when viewing the video sequence than when studying the individual frames.

The Appendix contains tables listing data for the area, width and height functions for all six notes. For complete spectral analyses of these functions, see Copley (1995, Chap. 4).

B. Side views

Figures 9–10 show measured trajectories for a central point on the upper lip. Figure 9 shows trajectories for the first five loud notes, and Fig. 10 shows trajectories for the first five soft notes. Very little motion was observed for the last note (A♭4), and what was observed could not be measured with confidence. Both figures have identical scales and all trajectories begin at the origin and progress as indicated by the arrows.

Recalling that the origin represents the place of maximum lip closure, it is interesting to note that the latter part of the trajectory takes the upper lip to points behind the point of maximum lip closure.

There is some degree of correlation among the loud tone trajectories. The overall shape of the trajectories is similar, but there is a decrease in relative longitudinal displacement with increasing frequency. In the parlance of some previously mentioned models, this confirms that the longitudinal "swinging door" motion is more pronounced at the lower frequencies and that the transverse "sliding door" motion becomes more important for higher frequencies.

The trajectories for the soft tones are less meaningful. As expected, the longitudinal and transverse displacement amplitudes are less than their loud counterparts, but there are no real similarities in trajectory shape. At best, the plots give some indication that the transverse and longitudinal displacements are approximately the same for a given softly blown note.

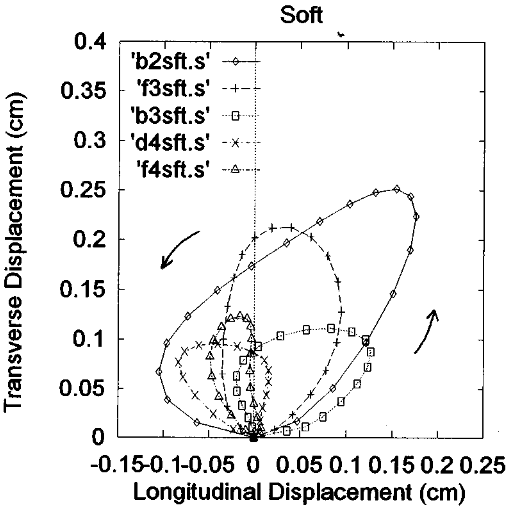

FIG. 10. Upper lip trajectories for first five notes played *mezzo piano*.

IV. GENERAL REMARKS

All of the above analyses apply to the data obtained from the one expert trombone player who served as our subject. For the sake of comparison, several student players were observed. Perhaps the most noticeable difference was the placement of the lips. The expert player's embouchure was situated such that the mouthpiece contained approximately two-thirds upper lip and one-third lower lip. In contrast, a wide range of upper lip to lower lip ratios were observed in the students. One student was observed to produce tones with virtually all upper lip. Despite the differences, the students' lips exhibited the same general trends as explained above. Casual analysis revealed slightly less regular lip openings and sometimes more or less penetration into the mouthpiece. It is quite possible that similar variations would be seen if data from several expert players were compared.

In conclusion, it is hoped that the data generated by this research will assist others studying and modeling lips in brass instruments. For this reason the detailed numerical values for lip area, height, and width are given in the Appendix. Because of their similarities, this research may be useful in the modeling of the other members of the brass instrument family.

ACKNOWLEDGMENTS

The authors wish to thank D. Bachelder for playing the trombone, R. Harris for use of the stroboscope, and W. Lifferth for preparing the mouthpieces.

APPENDIX. NUMERICAL VALUES FOR LIP AREA, WIDTH, AND HEIGHT

TABLE AI.

B♭2 - 117 Hz						
Phase (Degrees)	Area (cm^2)		Height (cm)		Width (cm)	
	f	*mp*	*f*	*mp*	*f*	*mp*
0	0.00	0.00	0.00	0.00	0.00	0.00
18	0.04	0.02	0.09	0.03	0.37	0.36
36	0.12	0.05	0.16	0.03	0.76	0.61
54	0.23	0.08	0.28	0.10	1.09	0.66
72	0.46	0.10	0.38	0.16	1.33	0.68
90	0.48	0.14	0.43	0.21	1.35	0.80
108	0.47	0.19	0.45	0.24	1.32	0.89
126	0.44	0.23	0.45	0.24	1.28	0.91
144	0.41	0.24	0.43	0.24	1.25	0.96
162	0.38	0.23	0.39	0.23	1.23	0.95
180	0.36	0.20	0.36	0.22	1.20	0.91
198	0.33	0.17	0.31	0.20	1.15	0.87
216	0.29	0.13	0.28	0.18	1.13	0.85
234	0.25	0.12	0.25	0.16	1.10	0.82
252	0.21	0.11	0.22	0.14	1.06	0.80
270	0.17	0.09	0.15	0.09	1.00	0.71
288	0.12	0.04	0.12	0.06	0.84	0.55
306	0.08	0.03	0.10	0.05	0.72	0.48
324	0.05	0.02	0.07	0.03	0.56	0.44
342	0.02	0.00	0.00	0.00	0.32	0.28

F3 - 176 Hz						
Phase (Degrees)	Area (cm^2)		Height (cm)		Width (cm)	
	f	*mp*	*f*	*mp*	*f*	*mp*
0	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.01	0.00	0.01	0.19	0.19
36	0.02	0.02	0.02	0.02	0.42	0.57
54	0.09	0.03	0.20	0.05	0.80	0.64
72	0.18	0.05	0.26	0.07	1.02	0.67
90	0.32	0.08	0.33	0.15	1.23	0.75
108	0.41	0.14	0.39	0.20	1.34	0.87
126	0.41	0.19	0.39	0.23	1.30	0.94
144	0.38	0.22	0.38	0.26	1.23	0.98
162	0.35	0.23	0.37	0.26	1.19	1.01
180	0.29	0.22	0.36	0.26	1.08	1.03
198	0.22	0.20	0.33	0.24	1.05	1.01
216	0.17	0.16	0.28	0.22	1.03	0.96
234	0.15	0.14	0.24	0.20	1.03	0.90
252	0.13	0.13	0.18	0.16	1.02	0.84
270	0.10	0.11	0.14	0.15	1.00	0.83
288	0.05	0.06	0.13	0.14	0.97	0.81
306	0.03	0.04	0.10	0.10	0.78	0.72
324	0.01	0.03	0.06	0.05	0.47	0.54
342	0.00	0.01	0.00	0.02	0.11	0.15

B♭3 -235 Hz						
Phase (Degrees)	Area (cm^2)		Height (cm)		Width (cm)	
	f	*mp*	*f*	*mp*	*f*	*mp*
0	0.00	0.00	0.00	0.00	0.00	0.00
18	0.02	0.01	0.04	0.01	0.45	0.30
36	0.07	0.02	0.10	0.03	0.88	0.48
54	0.19	0.03	0.19	0.04	1.11	0.58
72	0.30	0.04	0.31	0.05	1.22	0.65
90	0.33	0.05	0.32	0.06	1.25	0.69
108	0.34	0.07	0.33	0.09	1.25	0.72
126	0.33	0.10	0.33	0.14	1.22	0.77
144	0.32	0.12	0.32	0.17	1.20	0.83
162	0.29	0.13	0.28	0.17	1.17	0.84
180	0.24	0.13	0.25	0.17	1.11	0.84
198	0.19	0.13	0.19	0.16	1.07	0.85
216	0.15	0.12	0.16	0.15	1.03	0.84
234	0.11	0.10	0.14	0.11	1.00	0.80
252	0.09	0.07	0.10	0.08	0.96	0.73
270	0.06	0.05	0.07	0.05	0.86	0.70
288	0.03	0.04	0.05	0.03	0.58	0.66
306	0.02	0.02	0.03	0.02	0.38	0.52
324	0.01	0.01	0.01	0.01	0.05	0.37
342	0.00	0.00	0.00	0.00	0.01	0.19

TABLE AII.

D4 - 297 Hz						
Phase (Degrees)	Area (cm^2)		Height (cm)		Width (cm)	
	f	*mp*	*f*	*mp*	*f*	*mp*
0	0.00	0.00	0.00	0.00	0.00	0.00
18	0.02	0.00	0.05	0.00	0.39	0.20
36	0.06	0.01	0.10	0.01	0.75	0.38
54	0.11	0.02	0.18	0.02	0.98	0.49
72	0.18	0.03	0.23	0.03	1.08	0.58
90	0.24	0.05	0.27	0.05	1.14	0.62
108	0.27	0.06	0.28	0.09	1.17	0.68
126	0.26	0.07	0.27	0.11	1.16	0.78
144	0.24	0.08	0.25	0.12	1.12	0.78
162	0.22	0.09	0.22	0.14	1.09	0.80
180	0.20	0.09	0.21	0.14	1.03	0.81
198	0.17	0.08	0.18	0.12	1.00	0.85
216	0.12	0.07	0.14	0.08	0.97	0.87
234	0.10	0.06	0.10	0.06	0.94	0.84
252	0.08	0.05	0.08	0.05	0.92	0.77
270	0.05	0.04	0.05	0.04	0.80	0.71
288	0.01	0.03	0.02	0.03	0.46	0.67
306	0.00	0.02	0.00	0.02	0.20	0.58
324	0.00	0.01	0.00	0.01	0.00	0.39
342	0.00	0.00	0.00	0.00	0.00	0.10

F4 - 353 Hz						
Phase (Degrees)	Area (cm^2)		Height (cm)		Width (cm)	
	f	*mp*	*f*	*mp*	*f*	*mp*
0	0.00	0.000	0.00	0.000	0.00	0.00
18	0.00	0.010	0.01	0.010	0.20	0.20
36	0.02	0.015	0.03	0.030	0.37	0.43
54	0.03	0.020	0.05	0.040	0.44	0.48
72	0.04	0.025	0.08	0.050	0.55	0.52
90	0.06	0.045	0.09	0.070	0.81	0.62
108	0.09	0.055	0.10	0.080	0.96	0.68
126	0.15	0.060	0.18	0.080	1.07	0.73
144	0.20	0.065	0.23	0.080	1.13	0.75
162	0.20	0.065	0.20	0.075	1.13	0.77
180	0.18	0.065	0.16	0.070	1.11	0.80
198	0.16	0.065	0.15	0.065	1.08	0.83
216	0.13	0.060	0.13	0.060	1.04	0.84
234	0.12	0.050	0.12	0.055	0.98	0.76
252	0.11	0.025	0.10	0.050	0.94	0.57
270	0.09	0.020	0.09	0.040	0.84	0.48
288	0.04	0.010	0.08	0.025	0.72	0.44
306	0.02	0.005	0.04	0.015	0.56	0.38
324	0.01	0.005	0.01	0.010	0.47	0.30
342	0.00	0.000	0.00	0.005	0.19	0.18

(A♭4) - 410 Hz						
Phase (Degrees)	Area (cm^2)		Height (cm)		Width (cm)	
	f	*mp*	*f*	*mp*	*f*	*mp*
0	0.000	0.000	0.000	0.000	0.00	0.00
18	0.005	0.000	0.005	0.000	0.26	0.20
36	0.015	0.005	0.020	0.005	0.43	0.38
54	0.020	0.010	0.035	0.010	0.55	0.45
72	0.040	0.020	0.060	0.015	0.64	0.5
90	0.055	0.020	0.085	0.020	0.85	0.55
108	0.075	0.025	0.100	0.025	0.95	0.60
126	0.105	0.040	0.115	0.035	0.99	0.66
144	0.120	0.050	0.130	0.050	1.00	0.70
162	0.115	0.060	0.120	0.060	0.97	0.74
180	0.105	0.065	0.095	0.065	0.92	0.76
198	0.100	0.060	0.080	0.060	0.92	0.73
216	0.085	0.050	0.075	0.050	0.91	0.72
234	0.070	0.040	0.065	0.040	0.87	0.70
252	0.045	0.030	0.050	0.030	0.81	0.66
270	0.030	0.025	0.030	0.025	0.65	0.54
288	0.020	0.020	0.020	0.020	0.47	0.46
306	0.010	0.015	0.005	0.015	0.30	0.39
324	0.005	0.010	0.000	0.005	0.00	0.31
342	0.000	0.005	0.000	0.000	0.00	0.17

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