

Acoustical and physical dynamics of the diatonic harmonica

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The harmonica is arguably the most widely played instrument in the world, yet there is a surprising paucity of published studies of its acoustics or physical dynamics. The typical diatonic harmonica and the physical forces involved in its natural function are described, and simple observations of the harp's functions are reported. The speaking of the reeds, naturally, when producing a bend, and when speaking as an overblow or overdraw is discussed and investigated by simple stopping of the reeds, by videostroboscopic analysis, and by recording vibration of the reeds with displacement gauges. The reeds of the ten hole harmonica can be made to vibrate at varying frequencies depending on the size and shape of the player's vocal tract. Three different modes of speaking from each hole and its pair of reeds are revealed and studied: first, naturally in a closing mode, either blown or drawn; second, as a bend, either blown or drawn, with pitch in the interval between the two notes in the hole; and third, as an overblow or overdraw in an opening mode with a pitch outside the interval between the two natural notes of the hole. This dynamic interaction allows the player to speak with the instrument perhaps as with no other. © 1998 Acoustical Society of America. [S0001-4966(98)02404-7]

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INTRODUCTION

The name, *Harmonica*, has been used to designate many instruments over the years, some being reed instruments related to the instrument under discussion, and others seemingly unrelated, such as the glass harmonica attributed to Benjamin Franklin, which consisted of a set of glasses of varying size, tuned by varying the amount of water within. The modern harmonica—a.k.a. harp, mouth organ, French harp, Mundharmonica (in Germany), pocket piano, and Mississippi saxophone—is a descendant of instruments first reported and patented in the 1820's.¹ The principle embodied in the harmonica can be traced to the Orient where variations of the Chinese sheng existed for several millennia. All of these instruments use a vibrating free reed.

Structure and function of the harmonica

The active element of the harmonica is a metal reed with one end fastened to the surface of a thin metal plate; the other end is free to vibrate. All but the fastened end of the reed overlies a slot in the reed plate that is just large enough to allow the reed to vibrate freely in the slot [Fig. 1(a), (b)]. The reed is activated by the flow of air across it. It vibrates at a frequency which is near its natural (i.e., plucked) frequency. This frequency is determined by the mass and stiffness of the reed in cooperation with its associated acoustical system. The throttling action of the reed on the flow of air causes a periodic fluctuation of the otherwise steady air pressure provided through the mouth, thus creating sound.

The body of the harmonica is a comb, made of wood, plastic, or metal, with prongs separating a row of ten or more chambers. One plate of reeds, the *blow reeds*, which are

activated by positive pressure in the comb (i.e., blowing), is fastened to the top side of the comb with the reeds inside. A second plate of reeds, the *draw reeds*, which are activated by negative pressure, is fastened to the bottom side of the comb with the reeds outside. The reed slots on the blow- and draw-reed plates are arranged to coincide with each other on opposite sides of the chambers of the comb. Thin metal covers over the reed plates provide small resonating chambers which further modify the generated sound. The reeds can be arranged in various sequences of tones that encompass several octaves. Reeds of the popular ten hole, diatonic harmonica, tuned in the Richter model in a major key, are arranged as shown in Fig. 2. With this arrangement, one can produce the major chord of the key of the harp by blowing on any three adjacent holes. Drawing on the first four holes produces the dominant chord of the key. In order to accomplish this harmony, certain tones are omitted in the scale of the lowest and highest octaves, as can be seen in Fig. 2. The 10-hole diatonic harmonica has a range encompassing 3 full octaves, 22 diatonic tones, but since there are only 20 reeds in the 10 holes and 1 tone is repeated, there are 3 "missing" natural tones in the 3 octaves of the diatonic scale.

The arrangement of reeds in the typical diatonic harmonica is such that each of the three octaves is played differently. For the first six holes, comprising most of two octaves, the draw note is higher in pitch than the corresponding blow note. For these six holes, it is the draw note that can be *bent* down or flatted through air pressure and manipulation of the vocal tract by the player. For the remaining four holes, the blow reed is higher in pitch; here it is the blow note that can be bent. In each case, it is the higher note of the hole that

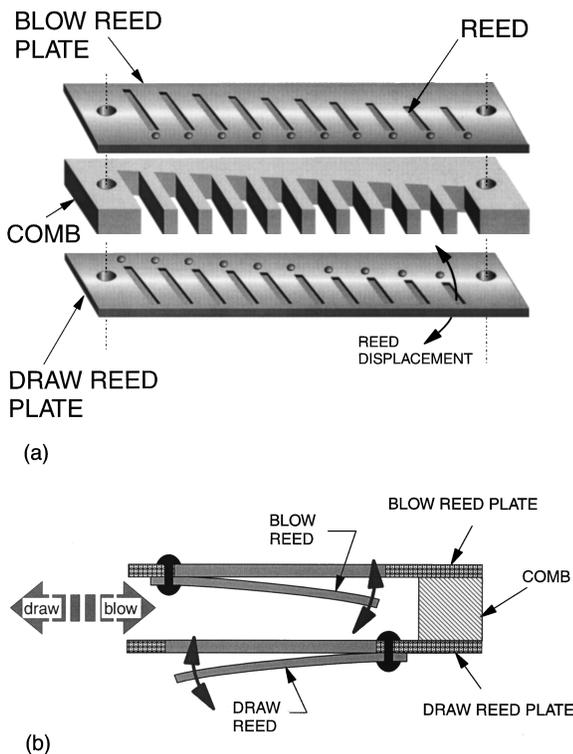


FIG. 1. (a) Exploded view of the ten hole diatonic harmonica showing the upper, blow reed plate, the lower, draw reed plate and the separating comb. Upper and lower covers of the reed plates are not shown. Reeds are mounted on the inside surface of the blow reed plate and the outside of the draw reed plate. Thus blowing closes the blow reed into the blow reed plate and opens the draw reed out of the draw reed plate. The reverse occurs on drawing. It is the closing reed that speaks on natural playing. (b) Schematic, cross sectional view of reeds and plates of a hole of a diatonic harmonica. Reeds vibrate in slots cut out of the reed plate. Blowing into the hole closes the blow reed and opens the draw reed. Drawing closes the draw reed and opens the blow reed.

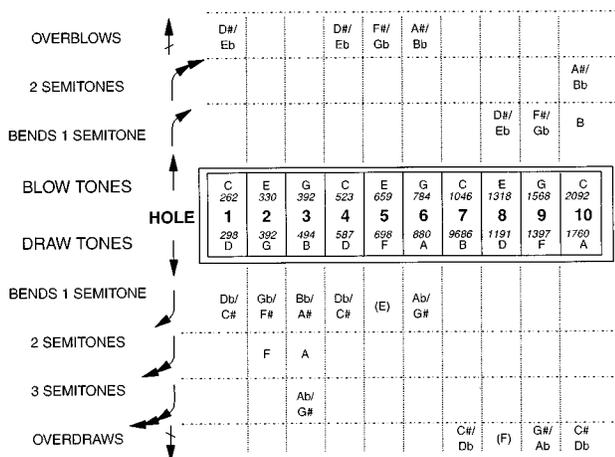


FIG. 2. Notes and approximate frequencies of a ten hole, diatonic harmonica, key of C. The upward arrow indicates blow; the downward arrow, draw. Blow and draw bends are indicated by bent shafts, up and down, respectively; number of semitones bent is indicated by number of arrow heads. Overblow and overdraw are indicated by slashed arrows.

appears to be bendable, whether blown or drawn. The often stated rule is that one can bend the pitch of the higher note in a hole down to a semitone above the lower note of the respective hole. It should be pointed out that bending produces virtually continuous pitch control within the interval between the blow and draw notes of the hole, in contrast to overblowing, to be discussed later.

In order to play the basic, natural tones of the key of the harp, no special configuration of the vocal tract is typically required. The player simply blows or draws through the appropriate hole. Vibration of the reeds occurs as a result of the interaction of aerodynamic forces acting on the reed and the mechanical properties of the reed itself. It is well known that a plucked reed will oscillate at a natural frequency determined by its mass distribution and stiffness. In order to cause self-sustaining oscillations, air must flow past the reed in a manner which reinforces this vibration. St. Hilaire *et al.*² have shown that such pressure instabilities could result when air flow is sufficient to cause boundary layer separation at the edge of the reed surface. When this occurs, the aerodynamic drag force on the reed increases as the gap decreases, and the reed moves against the air flow. Conversely, the drag force decreases when the gap increases, and the reed moves with the flow. This will thus inject energy into the reed motion, giving it a “kick.” This phenomenon can also be described in terms of acoustical impedance, as outlined by Johnston.³ The resulting frequency of oscillation will differ from the plucked frequency because of the coupling with the acoustical inertance and compliance of the air flow and airway of the player.

A reed vibrating in this fashion with the reed attached to the high pressure side of the reed plate and being forced primarily *into* the reed plate is said to function as a *closing reed*. Simultaneously the companion reed, overlying the same cavity but attached to the outer, low pressure side of its reed plate, is blown open. It vibrates only minimally when the natural note is played and functions as an *opening reed*. Consequently, the frequency of vibration of the opening reed is determined primarily by the closing reed. When the player blows through a hole, the blow reed is a closing reed, and the draw reed is an opening reed. When the player draws on the hole, these actions are reversed. Alternatively, one can define the blow reed as the reed which speaks primarily when the player blows through a given hole. The reverse occurs on drawing. The primary speaking reed is the closing reed in each case of simple blow and draw. (It is worth pointing out that despite the names, *opening* and *closing*, both reeds do in fact open and close their respective reed slots in the course of their vibration. Accordingly, this nomenclature convention unfortunately introduces some confusion. However, inasmuch as this designation is well established, we will adopt this terminology to designate the mode of operation of a particular reed.)

The discovery that missing notes of the diatonic scale and some notes of the chromatic scale can be fashioned by bending is attributed to the African-Americans of the southern United States in the last half of the nineteenth century. Modern instructions on this technique have been described as: “...draw in sharply, drop the jaw a bit, along with the

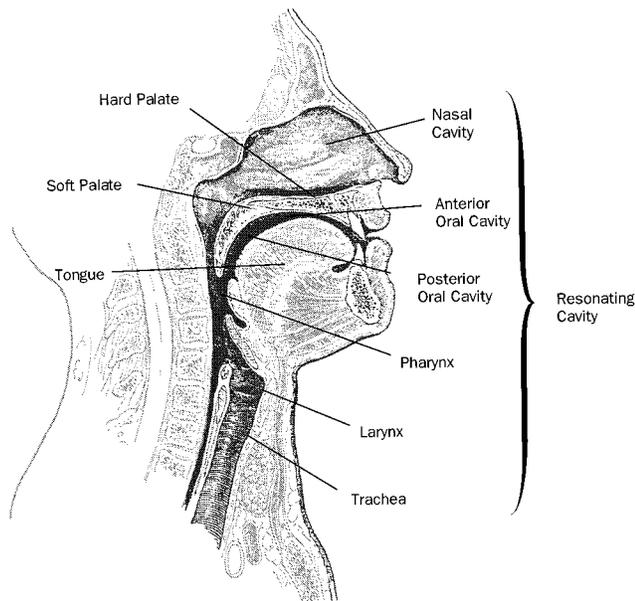


FIG. 3. Cross section of the vocal tract.

tongue, causing the air to dart downward to the floor of the mouth;⁴ “...suck the air through the harp towards the tip of [the] tongue;”⁵ “[inhale] with more force and [cause] the air stream to move to the bottom of the mouth and throat;”⁶ or, most descriptively, “[take] in air from your shoe.”⁷ Glover⁸ instructs that if one visualizes drawing a column of air, like a straw, over the tongue and throat, then bending consists of “bending that column of air down to the front part of [the] lower jaw.” Palmer⁹ relates that Sonny Terry’s technique was: “If you constrict the flow at any point along its passage from reeds to lungs, you change the resultant pitch of the reeds. Most harpmen choke the harp to achieve this effect. They narrow the opening in their throats to constrict the air flow....there is a simultaneous increase in pressure from the lungs.” Most practical is the advice of Baker,¹⁰ “...the tongue and throat movements when bending notes is (analogous to) different vowel sounds,... like forming AAH to OOH,... or EEE to OOO for the high notes.” We interpret these instructions as attempts to describe alterations of the volume and configuration of the vocal tract—here used to describe the lips, cheeks, mouth, pharynx, and trachea (Fig. 3). Unfortunately for the novice, the oropharyngeal configurations required in bending are not identical to any of those of normal speech.

There is an unfortunate dearth of reports in the scientific literature about the acoustics of the harmonica, or the physiology involved in playing it. Perhaps this is due to its humble nature, for there are many reports, and indeed volumes, on more “noble” instruments. In the nearly unique article concerning physics of the harmonica by Johnston,³ all of the references cited are to observations on other instruments, mostly woodwind and reed instruments. He cites no references to previous studies of the harmonica. Subsequent to Johnston’s article, in the second edition of *Harp Handbook*, 1991,¹⁰ Steve Baker described his experience based on simple observations and logical deductions, but his description lacks the benefit of vigorous scientific procedure. Our

studies elaborate on Baker’s observations and couple these with Johnston’s theoretical examination of the physical dynamics of harmonica reeds.

I. FUNCTION OF HARMONICA REEDS

A. Preliminary observations

Key to most of the expression on the harmonica is the ability of the musician to play a single note. Pursing the lips to the size of a single hole is the commonly used technique. Tongue blocking is another technique in which the lips cover several holes but the tongue blocks one or more of these holes. The player forces air through a hole on one or both sides of the tongue. Another method, curling the tip of the tongue into a tube that surrounds the hole, limits use of the tongue for other purposes, such as tongue blocking for octaves. However, curling the tongue permits playing with the covers of the harmonica removed. Consequently, the curled tongue technique was used in several of our studies. By such playing with the covers off and alternately stopping one or the other reed with a finger, one learns that stopping the draw reed while blowing has no effect on pitch and only a slight increase in loudness of the blown tone. This is most noticeable with more vigorous playing. The findings are reversed on drawing and stopping the blow reed. This suggests that stopping the reed that is not primarily speaking decreases the leak of air from the chamber, and that the natural blow and draw tones come predominantly from the blow and draw reeds, respectively. The other reed of the hole contributes minimally if at all.

As mentioned above, the technique of bending notes is perceived as a lowering of pitch as the player appropriately alters the vocal tract. Draw bends are obtained in the lower holes 1 through 6 where the higher pitched tone is drawn, and blow bends are obtained in holes 7 through 10 where the higher pitched tone is blown. Alterations of the vocal tract involved in bending tones principally consists of arching and/or thickening the tongue at various places along its length (anterior or posterior). This has the effect of altering the volume and shape of the resonant cavity.

So-called *overblow* and *overdraw* tones are a relatively recent addition to playing. Such tones can be elicited from all holes of the diatonically tuned harmonica (cf. Fig. 2), but they are used for holes 1, 4, 5, and 6 blow and 7, 9, and 10 draw to produce notes that are otherwise missing on the diatonic harmonica (a flatted third—holes 1 and 4 blow; a sharped fourth and a flatted seventh—holes 5 and 6 blow; a flatted second—holes, 7 and 10 draw; and a flatted sixth—hole 9 draw). Stringent control of breath and positioning of the player’s vocal tract are required in order to play overblow and overdraw tones. The novice attempting to play overblow tones can be very rapidly frustrated, for the consequence of an incorrect posture of the vocal tract is either silence, or an inharmonious sound. The first recording of such a tone is credited to Blues Birdhead (James Simons) in 1929,¹¹ but full use and perfection of the tones awaited the skill and persistence of Howard Levy who plays them with as much facility as he plays the bends. Consequently he is able to use the naturally diatonic harmonica as a fully chromatic instru-

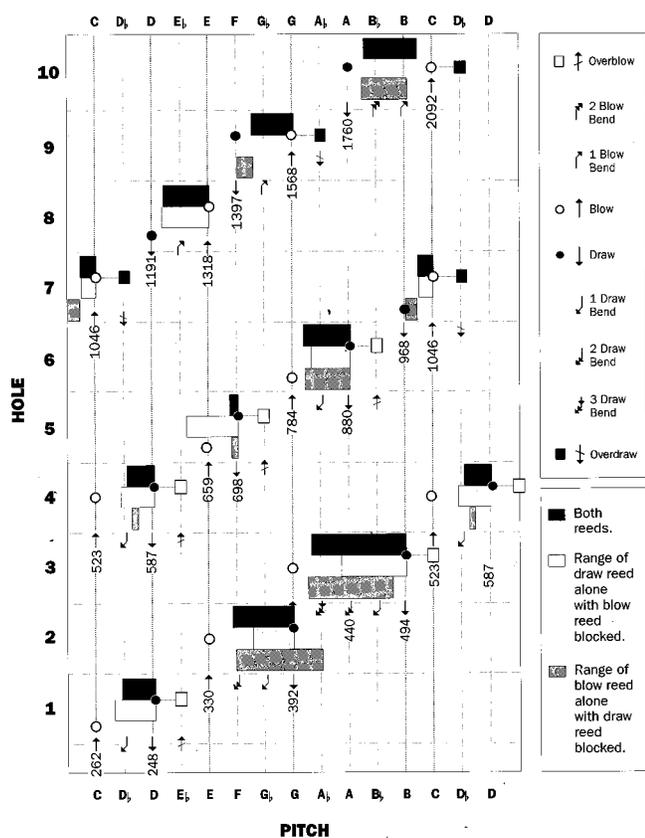


FIG. 4. Tones that can be modulated from blow and draw reeds together and alone on a Golden Melody Harmonica (Hohner) key of C, observed by blocking reeds with a finger. (+) and (−) indicate cents above or below the notes indicated along the abscissa. ○ is blow note, ● is draw note. Symbols otherwise are as in Fig. 2. Bars indicate range of frequency obtained by bending: black, straight with both reeds free; light gray, blow and draw bends with draw reed alone with blow reed blocked; dark gray (lowermost of the 3 bars), draw reed alone with blow reed blocked. Bars on holes 1–6 indicate draw bends, and on 7–10 blow bends. A more skillful player might increase the ranges with more precise configuration of the vocal tract. Note that both reeds are usually active with bends. Pure overblow and overdraw tones are obtained from a single reed (see overblows and overdraws for holes 1, 4, 5, 6, 7, and 9). Note that in holes 1 to 6 the draw note is higher pitched than the blow note, and bends are drawn. In notes 7 to 10 the reverse is true, i.e. the blow note is higher pitched than the draw note, and bends are blown rather than drawn.

ment. The resulting musical effects that this enables can be quite extraordinary.

The preliminary qualitative observations of reed motion with the covers off prompted a more rigorous investigation of reed and function. This was accomplished by three techniques: analysis of pitch production, videostroboscopic observation, and precision, noncontacting measurement of the displacement of the reeds.

B. Pitch production and reed primacy

Figure 4 illustrates the range of pitch that can be obtained from each hole of the diatonic harmonica as it is usually played, i.e., draw bending holes 1 to 6 and blow bending holes 7 to 10. The pitch was determined with a digital tuner (Korg, DT-2, Tokyo) and is expressed as cents above or below the targeted pitch. It is convenient to refer to harmonica reeds as functioning *primarily* and *secondarily*, because although actions of the blow and draw reeds are re-

lated, one reed usually dominates and is the *speaking* reed. Some simple initial studies were conducted to identify reed primacy by alternate blocking of one or the other of the two reeds of the hole while playing various notes—straight, bent, and overblown. Figure 4 also illustrates the range of pitch that can be obtained from each reed when the opposing reed of the hole is blocked. Within certain limits both reeds of a given hole can be induced to vibrate over a range of frequencies between the natural frequencies of the two reeds of a given hole.

When the blow and draw notes in the hole are two semitones apart, for example hole 4, the bent tone can be obtained from either reed with the proper configuration of the vocal tract. This suggests that the bent tone normally comes from either or both reeds, and that the reeds can be made to share primacy in producing the bent tones. When the tones in the hole are four semitones apart as in hole 3, the higher pitched reed (whether blow or draw) is primary for the first portion of the bend and lowering of pitch one semitone. When the full, three-semitone bend is obtained, however, the sound is produced entirely from the lower pitched reed which becomes primary. More specifically, the first semitone, draw bend of hole 3 (B flat on a C harp) is produced primarily from the draw reed. The second semitone, A, can be produced from either reed alone and is most easily produced by both together. The third semitone bend, A flat, comes from the lower pitched blow reed. Similar reed function is found in holes two and ten where the notes are three semitones apart. (In hole 10 the bend is a blow bend.)

The rule that one can bend the tone of a reed down to a semitone above the lower note in the hole is a convenient one for the player since that is what appears to happen. To be more accurate, however, one should recognize that primacy shifts to the lower pitched reed which is modulated up. Thus bends more properly must also be considered as involving an upward as well as downward modulation of pitch. Furthermore, when the higher pitched reed is blocked, it is possible to bend the lower pitched reed down. When the higher pitched reed is unblocked during one of these bends, the bent note is rapidly squelched.

Greater skill in bending allows wider range of control of all modes of reed action. A more skillful player might extend the range of bending beyond those shown in Fig. 4, as well might one do with a differently configured or tuned harp. Nonetheless, it appears that whether bending a tone up or down with both reeds free, the pitch can be bent most easily in the direction of the other note in the hole and is much more difficult (if not impossible) when the lower pitched reed is blocked.

In summary of these observations of reed function, it appears that both draw and blow bends involve both reeds to produce pitches in the interval between the natural pitches of the two reeds. The higher pitched reed bends down and the lower pitched reed bends up. The bent tone seems to come primarily from the reed with the natural pitch closest to the tone being played. There is more overlapping function of the lower pitched reeds, as in hole 3, than in the higher ones, as in hole 9. These conclusions require more quantitative validation. Accordingly, the speculation and subjectivity associ-

TABLE I. Stroboscopic examination of blow and draw reeds with various modes of playing. (+++) indicates vigorous action; (++) is moderate action, and (+) is minimal action. D Bend, DD Bend, and TD Bend indicate a draw bend, double draw bend, and triple draw bend respectively.

Hole	Action	Appx. note	Blow reed	Draw reed
1	Blow	C	+++	0
	Draw	D	++	+++
	D Bend	C#	++	++
	Overblow	D#	+	++
2	Blow	E	+++	0
	Draw	G	0	+++
	D Bend	F#	++	+++
	DD Bend	F	++	++
3	Blow	G	++	0
	Draw	B	0	+++
	D Bend	A#	+	+++
	DD Bend	A	++	++
	TD Bend	G#	++	+ to ++
Overblow	C	0	++	
4	Blow	C	++	+
	Draw	D	+	+++
	D Bend	C#	++	++
	Overblow	D#	0	+++
5	Blow	E	++	+
	Draw	F	+	++
	Overblow	F#	+	++
6	Blow	G	+++	0
	Draw	A	0	+++
	D Bend	G#	+++	0
	Overblow	A#	0	+++

ated with these preliminary observations that anyone can make can be elucidated by measurement of reed dynamics.

C. Stroboscopic evaluation of reed primacy

The above observations, obtained by blocking reeds, were confirmed by direct observation and by video recording the reed motion through a magnifying fiberoptic videoendoscope having a 70° angled tip (Nagashima) under stroboscopic illumination (Bruel and Kjaer, Rhinolarynx stroboscope, 4914). When the frequency of the strobe was offset slightly from the frequency of the tone being played, reed activity could be observed as a slow motion portrayal of its movement.¹² Analysis of the video tape recordings of such studies, summarized in Table I, shows that with simple blow and draw, the designated blow or draw reed vibrates freely while the secondary reed barely moves or vibrates minimally, the displacement being estimated at a twentieth or less that of the primary reed. At the beginning of a draw bend, the draw reed was observed to vibrate primarily, but as the tone dropped a whole tone or more, the blow reed began to vibrate and to become primary, even though the air flow continued to be drawn. In this mode, the blow reed functioned as an opening reed. Comparable observations were made with the blow bends. These shifts in reed primacy were most clearly seen in holes where the pitches of the blow and draw tones are more widely separated, as in holes 2 and 3 or

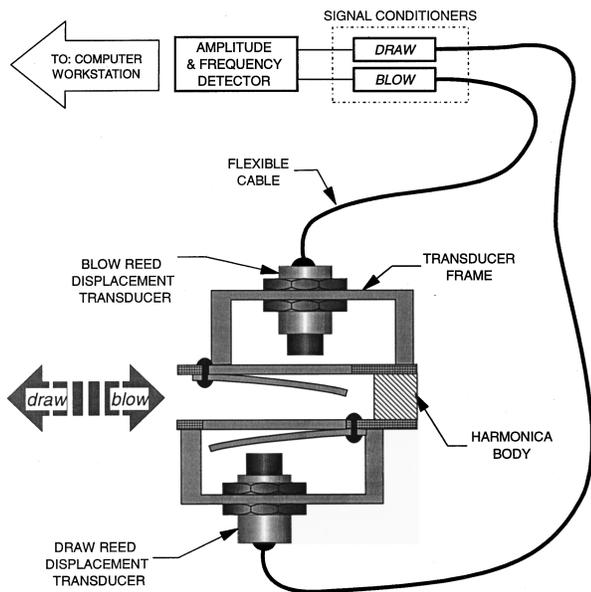
10. Somewhat similar observations were reported independently by Thaden,¹³ Baker,¹⁰ and other observant players.¹⁴

Overblows and overdraws are examples of things not being exactly what they seem on the harmonica. It would be logical to think, and was commonly believed, that the overblow notes come from the blow reed on which the player is blowing and that the pitch jumps up two or three semitones as one continues to blow. In actual fact, our simple, initial studies of reed blocking with a finger showed that the overblow tone actually comes from the draw reed of the hole which abruptly begins to vibrate as an opening reed, with a pitch that is only a semitone higher than the draw reed's natural frequency. Conversely, an overdraw tone was observed to come from the blow reed of the hole. In addition, stroboscopic analysis of the reeds during overblows showed that the blow reed becomes almost still, in spite of intensified vibration of the draw reed. Stopping the blow reed while playing an overblow tone also makes the tone purer, louder, and easier to hit. This observation led to the development of a modification of the typical diatonic harp that makes it easily fully chromatic.^{14,15} The pitch of both overblow and overdraw tones is outside the interval between natural pitches of the blow and draw notes of the hole, in contrast to bends which are almost completely within these intervals. Hence, there appear to be three modes of useful function of each reed: closing as in the natural modes of simple blow or draw, opening as in bending with the pitch within the interval of the two tones, and an overblow or overdraw as an opening reed with a pitch above that interval.

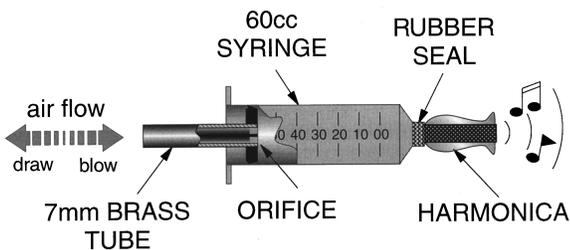
D. Reed primacy by dynamic vibration measurements

Dynamic measurements of reed vibration were performed to better quantify the observations obtained from the above stroboscopic evaluation. These experiments were conducted with a Hohner Golden Melody harmonica with covers removed, key of C, upon which were mounted two precision, noncontacting, proximity sensors (KD-2400, Kaman Instruments Corp., Colorado Springs), one over the blow reed and one over the draw reed. A specially constructed fixture allowed these sensors to be positioned to measure simultaneously the motion (displacement) of both the blow and draw reeds of any hole [see Fig. 5(a)]. The frequency response of the system was flat from DC to 10 kHz (± 3 dB). The output of the reed displacement transducers was recorded digitally at 10 000 Hz by a computer workstation (Apollo 3500, Apollo Computer Inc., Chelmsford, MA) which implemented high-speed data acquisition software (Significat, Hudson, MA). These signals were further processed in real time by a custom built circuit which measured the frequency and peak-to-peak amplitude of both signals of reed displacement. The latter data were recorded on a PC/386 with commercial acquisition software (LabTech Notebook, Laboratory Technologies, Inc., Wilmington, MA).

In addition to observations with simple oral playing, a resonating volume chamber was placed in the air stream adjacent to the harp [see Fig. 5(b)]. This device acted as a rudimentary equivalent of the vocal passage, similar to a system described by Johnston.³ With the simple plunger the volume of the resonating chamber was easily altered, and the



(a)



(b)

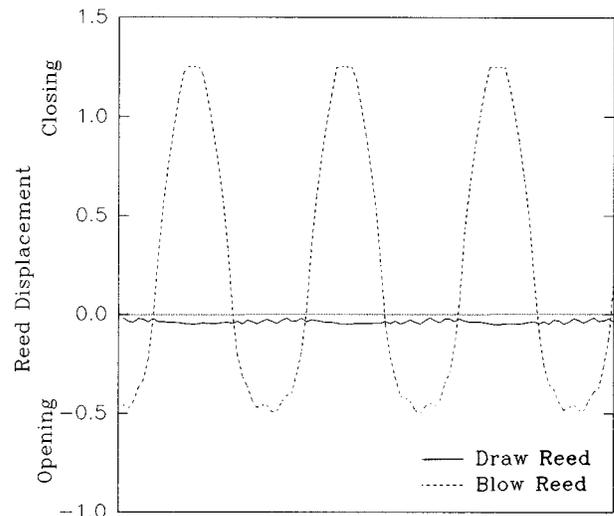
FIG. 5. (a) Schematic of experimental apparatus for measuring and recording reed displacement. (b) Sketch of variable resonating volume chamber (60-cc syringe) used to crudely simulate vocal tract, modified from device described by Johnston (Ref. 10).

reeds were made to vibrate in any of the three different modes of speaking (blow and draw; blow and draw bend; and overblow and overdraw) using regulated air pressure available in the laboratory.

Raw displacement data were displayed in compressed form in order to reveal the relative displacement envelope of the two reeds during various maneuvers (for example, see Figs. 7 and 12). The uncompressed display of the same data allowed detailed analysis of the shape of the trajectory of the individual reed displacement. The relationship between relative amplitudes and frequencies of the two reeds could be observed during bends and overtones from the real time display of the signal processor circuit.

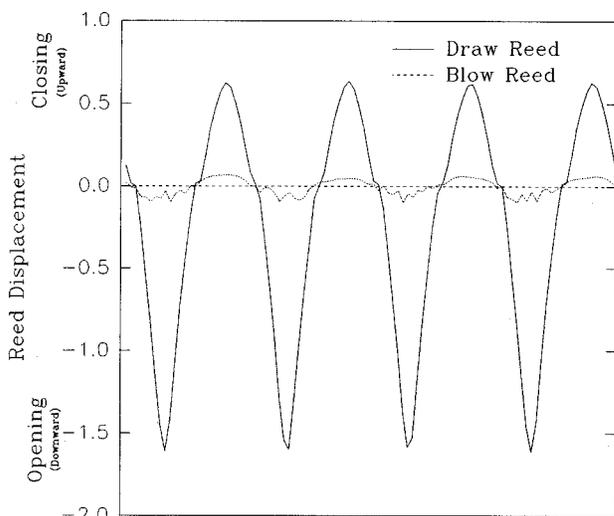
Measurement and display of reed vibration provided several qualitative observations as well as quantitative results. Although all 10 holes were studied, we present below detailed results for hole 3, which were taken to represent the general behavior observed for the remaining holes. It should be noted, however, that the two reeds of hole 3 provide a wider interval of tones than any other hole (six semitones from G, a straight note, to C, an overblow). Although unique, the hole appears to encompass all modes of action.

When a natural note was obtained by either blowing or



(a)

0.008 seconds



(b)

0.008 seconds

FIG. 6. (a), (b) Reed displacement with time for straight blow (a) and draw (b) notes on hole 3. Reeds move in parallel. Displacement values are relative only.

drawing, only the primarily speaking blow or draw reed was significantly active. There was only a minimal amount of the secondary reed vibration [Fig. 6(a),(b)]. This confirmed the observations made with the strobe light listed in Table I. In addition to the peak-to-peak amplitude of vibration, it was also informative to consider the relative displacement of the nominal position of the vibrating reed.

When playing a low blow note [such as 3-hole blow, Fig. 6(a)], the nominal, or "average," position of the blow reed moved away from the comb. In other words, the blow reed appeared to travel farther upward, into the reed slot, out of the comb, than downward. The draw reed, although nearly idle during blowing, appeared to displace slightly upward, into its respective reed slot and into the comb. The low draw notes [such as 3-hole draw, Fig. 6(b)] were characterized by a primarily closing draw reed, but the blow reed appeared to vibrate, albeit slightly, either about the nominal position or slightly away from the comb. The high blow and draw notes

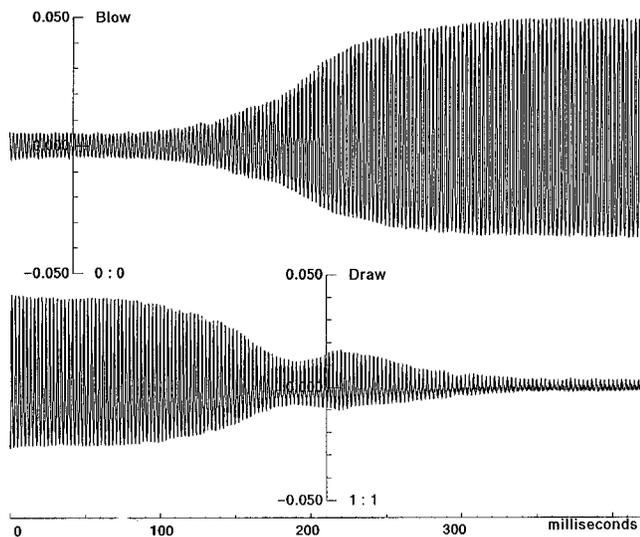


FIG. 7. Relative displacement of blow and draw reeds entering a bend on hole 2, from G to approximately F#. Note, the draw reed speaks initially and as a closing reed, but the blow reed takes over as an opening reed, as the player continues to draw but with a different embouchure.

behaved similarly, with roles reversed. These observations contradicted the intuitive prediction that the nominal position of both reeds of a hole should move outward on blowing with positive pressure in the hole and inward on drawing with negative pressure in the hole.

Intuition would likewise dictate that the relative phase between the two reeds would result in their contrary motion: outward with blowing and positive pressure in the hole and inward with drawing and negative pressure in the hole. However, this was observed to be the case only for the high blow notes. When any of the ten holes was drawn, the reeds were observed to oscillate in parallel with one another. Since the draw reed did not vibrate appreciably for the low blow notes, it was difficult to distinguish the relative phase. Parallel motion of reeds can be interpreted as both reeds acting simultaneously to close, or open, their respective reed slots. The level of pressure also appeared to bear a slight influence on the phase relation for some of the holes. For example, when high pressure was applied on the 3-draw or 3-draw bend, the motion of the closing reed was observed to lag slightly further behind the opening reed.

The displacement patterns of the blow and draw reeds displayed disparate degrees of departure from simple harmonic motion. In most cases, the blow reed appeared to follow a sinusoidal trajectory, whereas the draw reed displayed a notable amount of superimposed third harmonic (second overtone; see Figs. 6(b) and 8, for example). The degree of departure of both displacement patterns from a sinusoidal shape was more prominent for higher air pressure and flow (not shown in figures) than for lower pressure and flow.

Dynamic measurements of reed displacement were recorded while *entering* and *exiting* a 3-draw-bend (3DB). A compressed view of the reed displacements upon entry to the bend is demonstrated in Fig. 7. As the bent note was established, the amplitude of vibration of the (higher pitched) draw reed gradually diminished in favor of increased vibra-

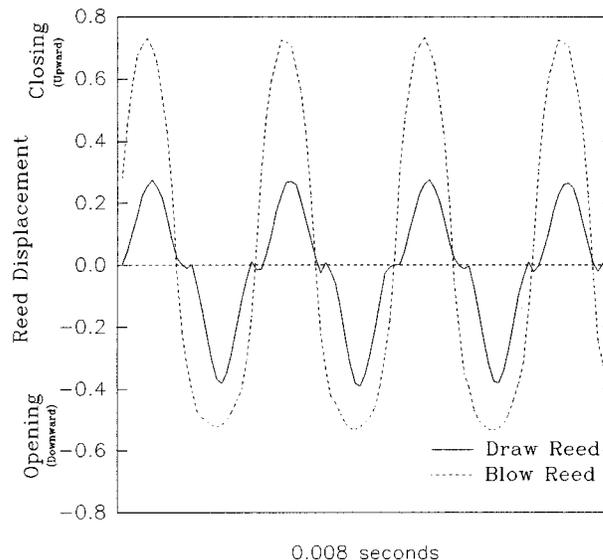


FIG. 8. Relative displacement of blow and draw reeds during a two-semitone bend of hole 3. Note significant vibration of both reeds, and parallel motion of the reeds.

tion of the blow reed. A detailed view of reed displacement at the point of a two-semitone bend (low A on a C harp) is shown in Fig. 8. Comparison with the pure blow and draw waveforms demonstrates that the bent note results in an almost composite of the two. The wave shapes and relative position of both the blow and draw reed displacements were observed to resemble those occurring for their respective straight notes. (This is worthy of recognition since the blow reed is no longer operating as a closing reed, but operates as an opening reed.)

Figure 9 depicts data for hole 2 played by mouth as a double draw bend is entered. The amplitude of vibration is plotted as a function of frequency. With proper configuration

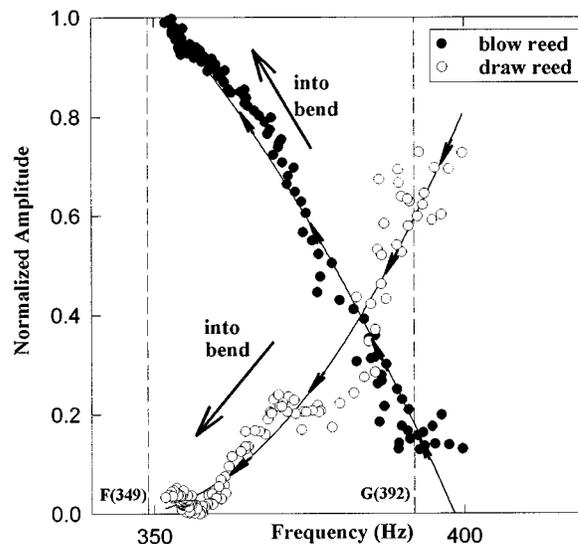


FIG. 9. Amplitude of reed displacement versus frequency while entering a double draw bend from a straight draw on hole 2 of a 10 hole diatonic harmonica. As frequency decreases, the amplitude of vibration of the draw reed decreases as the amplitude of the blow reed vibration increases.

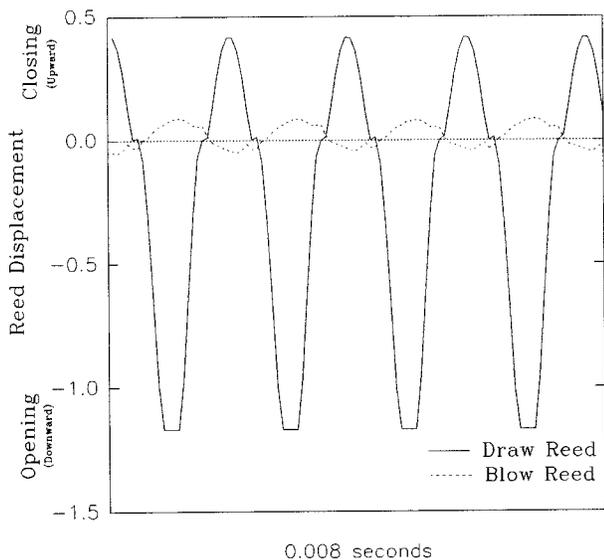


FIG. 10. Relative displacement of reeds with overblow on hole 3. Almost all action is on draw reed. (Clipping of waveform at bottom is due to saturation of the amplifier.)

of the vocal tract, a wide range of pitch was possible, confirming observations shown in Fig. 4. As the bend was entered and frequency dropped, the amplitude of vibration of the draw reed diminished while the amplitude of the blow reed increased. Thus the act of bending appeared to divert or transfer the reed activity from the draw (closing) reed to the blow (opening) reed.

The nominal positions of the reeds during the low draw bends (holes 1 to 6) were somewhat counter-intuitive. The nominal position of both reeds was displaced *away* from the comb [see Fig. 6(a), for example]. In other words, the maximal outward excursion of the reeds was surpassed by their maximal inward excursion—counter the principal air flow and against the primary pressure gradient. The high note blow bends (holes 7 to 10) did not evidence such anomalous behavior. However, for both draw bends and blow bends, counterintuitive parallel motion of the reeds was demonstrated. Most intriguingly, this did not occur in holes 9 and 10. As with the straight notes, the phase relation between the reed motions was observed to depend on the magnitude of air flow. Particularly, for the low draw bends, it was possible to achieve phase from 0 degrees (parallel motion) to 90 degrees phase lag between the reeds, depending on the intensity of the tone.

It was possible to obtain overblow tones with the volume-chamber apparatus, in most instances with a small volume. The overtones achieved in this fashion were observed to occur abruptly, as they do with normal playing of overblow notes. The transition from blow to overblow would “pop” into place as one changed the volume rather than slide smoothly, as is characteristic of the bent tones. The apparatus allowed more pure and complete overblows to be achieved than could be obtained with oral playing. Figure 10 shows the detailed waveforms of reed displacement for a sustained hole-3-overblow. The minimal activity of the blow reed noted here was not always easily obtained and sustained when the harp was played by mouth. For all holes studied,

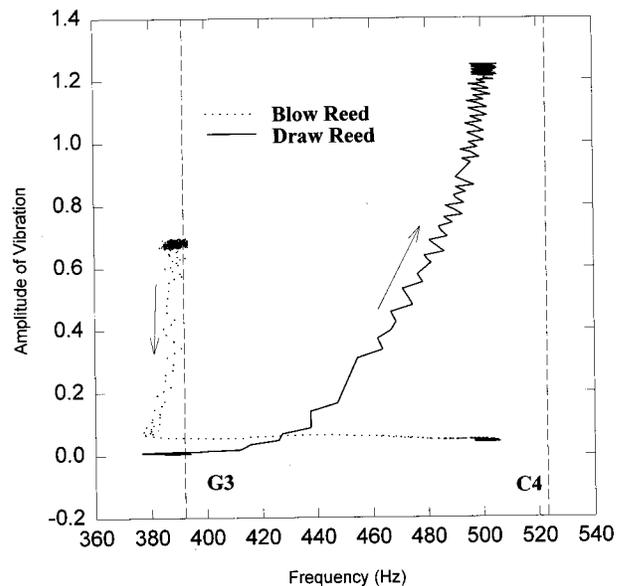


FIG. 11. Relative displacement of reeds during onset of overblow on hole three (not used in normal playing). Note: blow reed, with pitch of G, speaks initially but abruptly becomes silent as the draw reed, with natural pitch of B, speaks with (overblow) pitch of C.

the nominal position of the reeds was observed to move outward with respect to the comb, concurrent with the air flow. This was especially true for the vigorously vibrating draw reed.

The relative phase of the reeds for the overblows studied (hole 3 to 6) was observed to depend upon the location of the displacement transducer. When placed near the roots of the two reeds of hole 5 and 6, the phase relation evidenced parallel motion; whereas, when placed at the tips, the motion was in opposition. The opposite was true for hole 4. Hole 3 was inconclusive due to the negligibly small amplitude of vibration of the blow reed.

The distinguishing characteristics of the overblow as compared to the bend are further illustrated by comparing the amplitude versus frequency plot of an overblow (Fig. 11) with that of a bend (Fig. 9). Unlike the bend, which displays a smooth and gradual transition of reed primacy as the frequency changes, the overblow demonstrates a much sharper drop in the amplitude of oscillation of the closing, blow reed and simultaneous rise in amplitude of oscillation of the opening, draw reed. The interval between natural frequencies of the two reeds is far more devoid of activity in the overblow as compared to the bend.

The resulting overlap in frequency response of the two reeds during bending allows the player not only to bend more easily, but to slide between bent and straight notes. Consequently, this provides more opportunity to introduce expression into the notes being played. An example of this is depicted in Fig. 12 which shows a tracing of the amplitude of reed vibration compressed in time and recorded during a 6-draw to 6-draw-bend, played by Howard Levy.

In some cases, it was possible to obtain, and maintain, a dissonant overblow. In this case, the vibration of the two reeds remained synchronized but assumed different fundamental frequencies. Figure 13(a) and (b) shows, respectively,

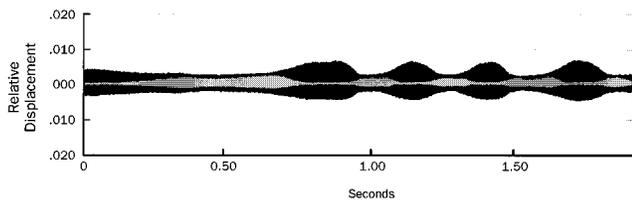


FIG. 12. Relative displacement amplitude of blow and draw reeds during several partial entries and exits of hole 6 draw bend. Note reciprocal shifting activity of the two reeds. Note the blow reed is the dominant actor in the draw bend, as indicated in Table I.

a consonant and dissonant overblow obtained in hole 3. In the case of the dissonant 3-overblow, the draw reed, with a natural pitch of B (494 Hz), was induced to vibrate at 518 Hz, but the blow reed with natural pitch of G (392 Hz) vibrated at 358 Hz (approximately F) with an apparent 25% modulation in its period from cycle to cycle. In a consonant overblow, the draw reed was observed to vibrate at 523 Hz (C_5) and the blow reed vibrated at the same frequency but with diminished amplitude. In normal oral playing such dissonance is common during overblows, and is produced even more frequently by less skillful players.

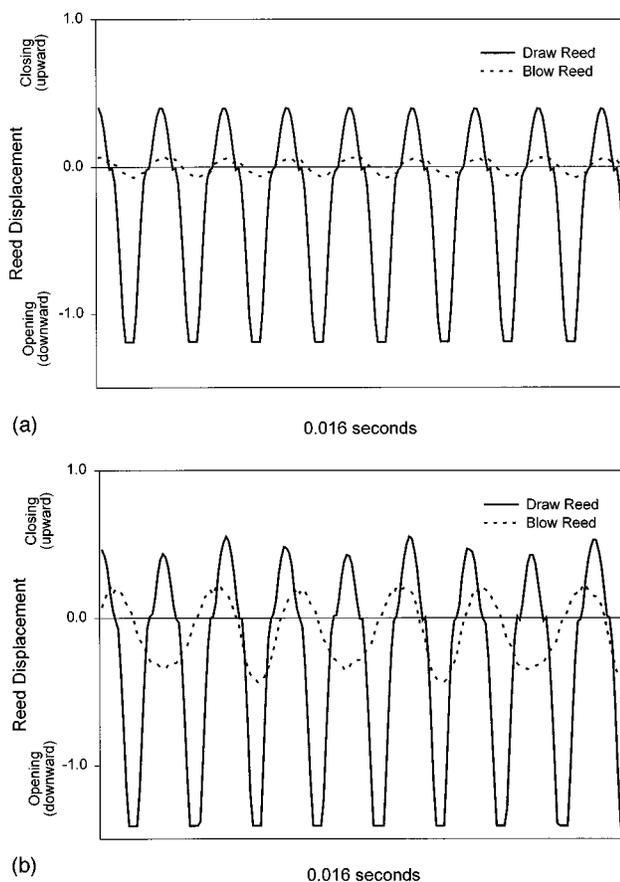


FIG. 13. (a), (b) Relative vibration of reeds during a consonant (a) and dissonant (b) overblow on hole 3. During the dissonant overblow, the draw reed, with a natural pitch of B (494 Hz), vibrated at 518 Hz, but the blow reed with natural pitch of G (392 Hz) vibrated at 358 Hz (approximately F) with an apparent 25% modulation in its period from cycle to cycle. In a consonant overblow, the draw reed vibrates at 523 Hz (C_5) and the blow reed vibrates at the same frequency but with diminished amplitude.

II. DISCUSSION

For over a century harmonica players have manipulated the harmonica to produce a wide variety of tones, glides, and slurs. The resulting effects reflect the dynamic interplay of physics and acoustics of the harmonica coupled to the body of the musician.

To understand the dynamics of music production with the harmonica it is essential to understand the behavior of the instrument. In these studies we have focused on the dynamics of the reeds themselves and of their function as a player achieves desired notes through the combination of blowing, drawing, bending, overblowing, and overdrawing. The information obtained has shown how an array of sounds can be accurately produced with a single channel and a pair of reeds. For example, in the third hole of the popular diatonic harmonica, two natural notes (blow and draw), one-, two-, and three-semitone bends, and an overblow can be produced with the two reeds by alteration of the vocal tract of the player. The new group of tones introduced in the last quarter century, namely overblows and overdraws, have been shown to be effected primarily by only one reed which functions as an opening reed—the normal function is closing—at a pitch outside the interval of the two notes in the hole. Better understanding of these new tones provided the motivation for the authors to undertake the studies described here.

The common rule that bent notes are limited to within a semitone of the opposite note of the hole was substantiated in these studies. This is partially explained by the theoretical model of Johnston which describes the range of pitches which are producible from a single reed. His analysis demonstrated that closing reeds can be flatted a semitone or so below their natural resonant pitch. Johnston's theoretical model unfortunately did not account for this possible coupling between the two reeds. The reed-blocking experiments reported above demonstrated that the presence of a lower pitched, opening reed in the same hole appeared to diminish the potential range by imposing a lower limit on the bend. Similarly, the presence of a *higher* pitched opening reed was found to virtually obliterate the blow bend of the closing reed in holes 1–6 and the draw bends in holes 7–10.

Due to the simplifying assumptions associated with Johnston's model, it is also not capable of accounting for many of the nuances of the construction of the harmonica itself. Therefore, additional modeling will be necessary in order to understand how the geometry, physical properties, and air flow combine to produce the observed phenomena involved in producing tones on the harmonica. In spite of this instrument's apparent simplicity, there is a multitude of modifications that have been introduced, or proposed, to alter the timbre and improve the ease of achieving certain notes. The aerodynamics associated with increasing the reed plate thickness, the shape of the air hole in the comb, or the orientation of the reed pairs, for example, would make an interesting topic of study if a more elaborate mathematical model were developed.

Our quantitative measurements of reed dynamics help substantiate some of the suspected relationships between reed primacy and the fundamental tone that is generated. Since the trajectory of the reed determines the flow of air, the

fundamental frequency of the reed displacement determines the frequency of the tone that is generated. However, the reed motion was observed to contain overtones. The cause of this distortion could be explained by the nonlinearity of either the displacement measurement system or the reed oscillator itself. In the case of the draw reed, a significant inflection in the displacement tracing occurred in close proximity to the zero-crossing point of the reed with respect to the reed plate. The calibration of the displacement transducers did not reveal any discontinuity at the zero-crossing point which could explain this inflection. Accordingly, this “hesitation” in the reed motion is most likely caused by either the aerodynamic disturbance or instability of the jet of air which results in the constricted reed slot.²

The paradoxical behavior observed with respect to the parallel motion of some of the reed pairs may appear counterintuitive and initially seems to contradict the fact that the blowing pressure or drawing pressure causes one reed to open when the other one closes, and vice versa. However, it can be explained through the small-signal theoretical model of Johnston³ which predicts the relative phase of the reed motion with respect to the acoustic pressure in the hole. As would be expected from a nonlinear dynamic system, the phase relation at higher amplitudes (greater pressure or air flow) was observed to differ slightly from the low amplitude response. In particular the closing reed was observed to lag slightly further behind the opening reed for the draw and draw-bends when high pressure was applied. The slight variation of phase observed in response to increased air pressure can easily be explained by the well-known influence of damping on resonant frequency and phase angle; see Ref. 16, for example.

Care was taken to position the displacement sensors consistently in a similar relative location along the length of each of the reeds. The finite spatial resolution of the sensor resulted in an averaging effect of the displacement measurement. For most of the reeds studied, the shape of the displacement trajectory did not appear to depend upon the location of the transducer. However, the overblow in hole 3 and 6 did demonstrate such a dependence. This observation can be taken to imply that one, or both of the reeds during these overblows assumes an inflected shape. This would further imply that an overtone would be present. Basic beam theory would predict the frequency of this overtone to be 6.26 times the fundamental.¹⁶ The absence of this observation for the other maneuvers could be attributed to the absence of this overtone or to the limited spatial resolution of the sensor, as mentioned above.

The counterintuitive observations relating to the nominal position of the reeds may be understood by considering the effect of air flow velocity upon the local gradient of pressure. According to the Bernoulli principle, increased velocity along a streamline of the flow, for example created by the constriction between the reed and reed slot, causes the pressure to decrease; therefore, it is possible to create a partial vacuum with positive flow. These results also shed some light as to the influence of reed offset upon ease of achieving desired notes. The common practice of adjusting the resting position of the reed, or reed offset, by gently bending the

reed into or out of the plate may, in effect, relocate the reed to an equilibrium position more amenable to bending or overblowing/overdrawing—but at the expense of increasing the difficulty of playing the natural tone.

The graphs of amplitude versus frequency of reed vibration that were generated during bent, overblown, and overdrawn notes were quite informative for demonstrating the distribution of reed primacy. As the linear acoustical model of Johnston³ would theoretically predict, the process of bending involved a smooth transition of primacy, whereas the overblows and overdraws demonstrated a more discontinuous, sudden jump in primacy.

The harmonica is nearly unique among musical instruments in that the vibrating oscillator, the reed, which produces the sound, is alternately upstream and downstream from the controlling resonating volumes. We have attempted to qualify and quantify some of the phenomena of reed function as the reeds react to this acoustical coupling. Johnston,³ who provided the first scientific study of this phenomenon, demonstrated that changes of pitch are effected by altering the acoustic impedance of the vocal tract, which in turn drives both reeds of the channel of the harmonica.

Similarly, the present investigation has centered primarily on the harmonica itself. However, in order to understand the dynamic function of harmonica playing, the human vocal tract must also be studied. Clinch and associates¹⁷ have shown with the clarinet, saxophone, and recorder that for good quality notes resonant frequencies of the vocal tract must match the frequency of the desired note. The harmonica requires pitch control of another order, for the acoustic impedance of the vocal tract controls not only quality of tones but it also raises or lowers the pitch in order to achieve certain notes. A wide variety of air flow rates, vocal cavity volumes and vocal configurations are compatible with the production of natural tones from the harmonica. To produce a more pure natural tone requires not only adequate shape of the vocal tract, but good musical sense and a sensitive auditory-vocal feedback mechanism. It appears that the volume and shape of the vocal tract have only a slight effect on the natural tones, but the mode and frequency of the fashioned notes—bent, overblown, or overdrawn—are caused by changes in the vocal tract.

In a preliminary study of one aspect of the vocal tract, namely the volume of the oral cavity, a simple experiment was conducted in which a player, lying supine, played specific fashioned notes and then held the configuration of the vocal tract while the oral cavity was filled with water and the required volume was recorded. Reproducible results were obtained with practice. The results of this preliminary experiment are shown in Fig. 14. It is probable that actual playing volumes were larger than measured, since when water was instilled, constriction of the glossopharynx and larynx occurred in order to suppress the swallow reflex and prevent aspiration. The volume of the anterior oral cavity was found to be inversely related to pitch as modified by bending. This relationship was not found with the straight notes which could be obtained with a wide range of airway volumes. Changes in configuration of the oral tract, however, determine the timbre of notes, which is a subject of further study.

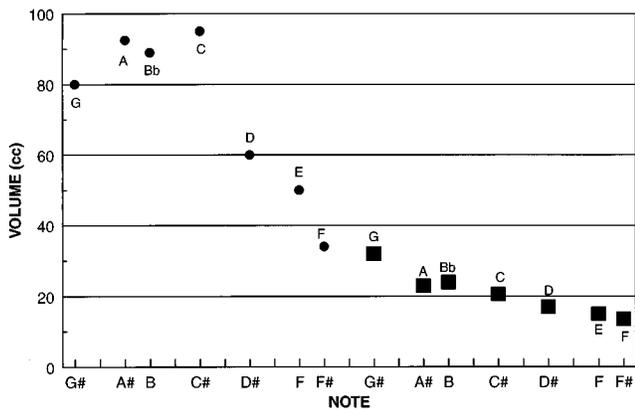


FIG. 14. Volume of oral tract used to play the scale with 1 and 4 draw bends. Harps keyed in the scale of F were used on which hole 1 draw bend (circles), or for the higher scale, hole 4 draw bend (squares) were played. The resulting scale is in the key of F#. The player held the configuration of the vocal tract as the volume of water required to fill the oral cavity was introduced and measured. Pitch of notes was inversely related to volume.

Upon delving into the physics and physiology of harmonica playing, the extent of the unknown phenomena concerning this instrument became increasingly evident. Each experiment, more times than not, revealed new ground yet unexplored. The authors now realize that this report does not include many of the additional features of sound affecting the timbre, modulation, or voicing. Most notably absent in these studies was the use of cupping of the hands. Most harpmen will use this technique to introduce vibrato and other forms of expression, as well as to alter the timbre of the sound. The answer to these and other questions regarding the physiology of harmonica playing will be further elucidated through systematic analysis of coupled interaction of the harmonica with the vocal tract—as revealed by videoendoscopic, ultrasonic, and fluoroscopic imaging.

III. CONCLUSION

Artistry of harmonica playing is related to the interplay between the player and the instrument. In this project, the physical behavior of the reeds of the harmonica was investigated. Mechanical and acoustic aspects of reed dynamics were elucidated during blowing and drawing, overblowing and overdrawing, and blow and draw bending. Through knowledge of reed function, the artistry and process of “speaking” with the harmonica can be better understood, and possibly mastery of this instrument will be enhanced.

In the final analysis, the music created by the harmonica consists of more than the acoustic and physical function of

the reeds. There is a synergy which causes the whole to be greater than the sum of the component parts and an artistry which cannot be quantified—dynamics which give personality to the instrument, reflecting individuality of the musician. As with speech which varies from person to person, there are certain tonal elements of harmonica playing which are similarly individualized. This dynamic interaction allows the player to speak with his instrument perhaps as with no other. Just as no two voices are exactly alike, each player imparts his own timbre, and one cannot expect to emulate exactly the musical tonality of another. This helps keep the harmonica interesting, and indeed has helped to sustain its enduring prominence throughout the world

ACKNOWLEDGMENTS

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