feature article

# Acoustics of free-reed instruments

James Cottingham

**Documents dating back to before 1000 BCE describe a wind instrument whose reed vibrates back and forth across the frame that houses it. Nowadays, free-reed instruments inspire both scholarly study and musical innovation.**

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**Free-reed instruments** fall into two related but distinct families: Asian mouth organs of ancient origin and Western instruments that originated in Europe about 200 years ago. The Western free-reed instruments include the harmonica and the "squeezeboxes," the various forms of accordion and concertina. In their relatively short lifetime, those instruments in particular have come to be employed in almost all genres of music and, throughout the world, are among the most widely played. Yet until the late 20th century, only a small amount of acoustical research focused on free-reed instruments. During the past two or three decades, however, interest has surged, and researchers in musical acoustics have devoted a much greater amount of attention to them. To be sure, more papers are written about the trumpet, clarinet, and the violin. But an indication of the increase in research interest in free reeds in the 1990s is the inclusion of a section in the second edition of *The Physics of Musical Instruments* (Springer, 1998), by Neville Fletcher and Thomas Rossing, that provides a summary of the research. The first edition of seven years earlier had no such section.

The Asian family comprises a multitude of wind instruments. Among the most familiar are mouth organs, including the *sheng* of China (a modern version of which is shown on the cover of this issue), the *sho* of Japan, and the *khaen* of Thailand and Laos.[1] In some of them, a single pipe is fitted with a single free reed and a musician uses finger holes to change the pitch. In those cases either the mouth of the player or a gourd wind chamber envelops the reed. Perhaps more common are multipipe configurations in which each of several pipes fitted with a free reed sounds a single note. Those instruments are constructed so that all the reeds are in a single wind chamber. Each pipe has a hole located at a point that destroys the pipe resonance; thus the pipe does not sound unless the hole is covered by the musician's finger. For either class of instrument, the pipes may be open at both ends or closed at one end. Often they are sounded by two directions of airflow, corresponding to the player's inhaling or exhaling.

The extent to which the Asian free-reed instruments inspired the newer European ones is a matter of historical uncertainty. In any event, the Western family of instruments, in addition to the harmonica and the squeezeboxes, contains the various types of reed organ, including the parlor organs that were popular in North America in the late 19th and early 20th centuries, the harmonium, and the small versions of the harmonium that came to be used in certain kinds of Indian music. Unlike most other wind instruments, the Western free-reed variety generally do not employ pipe resonators.

This article looks at some of the main acoustical properties of Eastern and Western free-reed instruments. The research on them, both experimental and theoretical, has focused on three important areas: the basic mechanisms of reed oscillation and sound production, the influence of resonators on tone quality, and the influence of resonators on pitch. Of particular interest is pitch bending, especially notable in harmonica music. The box below provides links to websites that give the history of free-reed instruments and examples of what they sound like.

## Free and beating reeds

The term "free reed" and its definition may well be less familiar than the instruments themselves. What, then, is a free reed, and why is a harmonica reed "free" and a clarinet reed not? As shown in figures 1a and 1c, a free reed is a vibrating tongue constructed or mounted in a way that allows it to vibrate back and forth through its reed plate or frame, much like a swinging door. In contrast, the so-called beating reed in an instrument such as the clarinet is slightly wider than the opening over which it is mounted. The remaining panels of figure 1 show examples of actual free reeds, along with their instruments.

The principal acoustical difference between the Western and Asian free-reed instruments is in the design of the reeds. The Western instruments employ reeds in which a separately

### Images and sounds

With a little effort, you can find pictures of free-reed instruments and innumerable sound and video files on the Web. Not only will you encounter harmonicas, accordions, and harmoniums producing all styles of music, but you'll see more examples of *khaen* playing than a person unfamiliar with the instrument might expect. There is no point in attempting to give a comprehensive list of useful sites, but following are a few sources of information directly related to topics in this article.

- Pat Missin's website, http://www.patmissin.com/history/history.html, links to good summaries of the history of both Asian and Western free-reed instruments, with numerous photos and sound examples. The excerpts played on the Asian mouth organs may be particularly valuable for listeners unfamiliar with those instruments.
- Readers interested in experiencing the limits of pitch bending in harmonica playing can explore the website of Howard Levy at http://www.levyland.com.
- To learn more about the pitch-bending accordion and hear sound examples, visit Tom Tonon's website at http://www.bluesbox.biz.

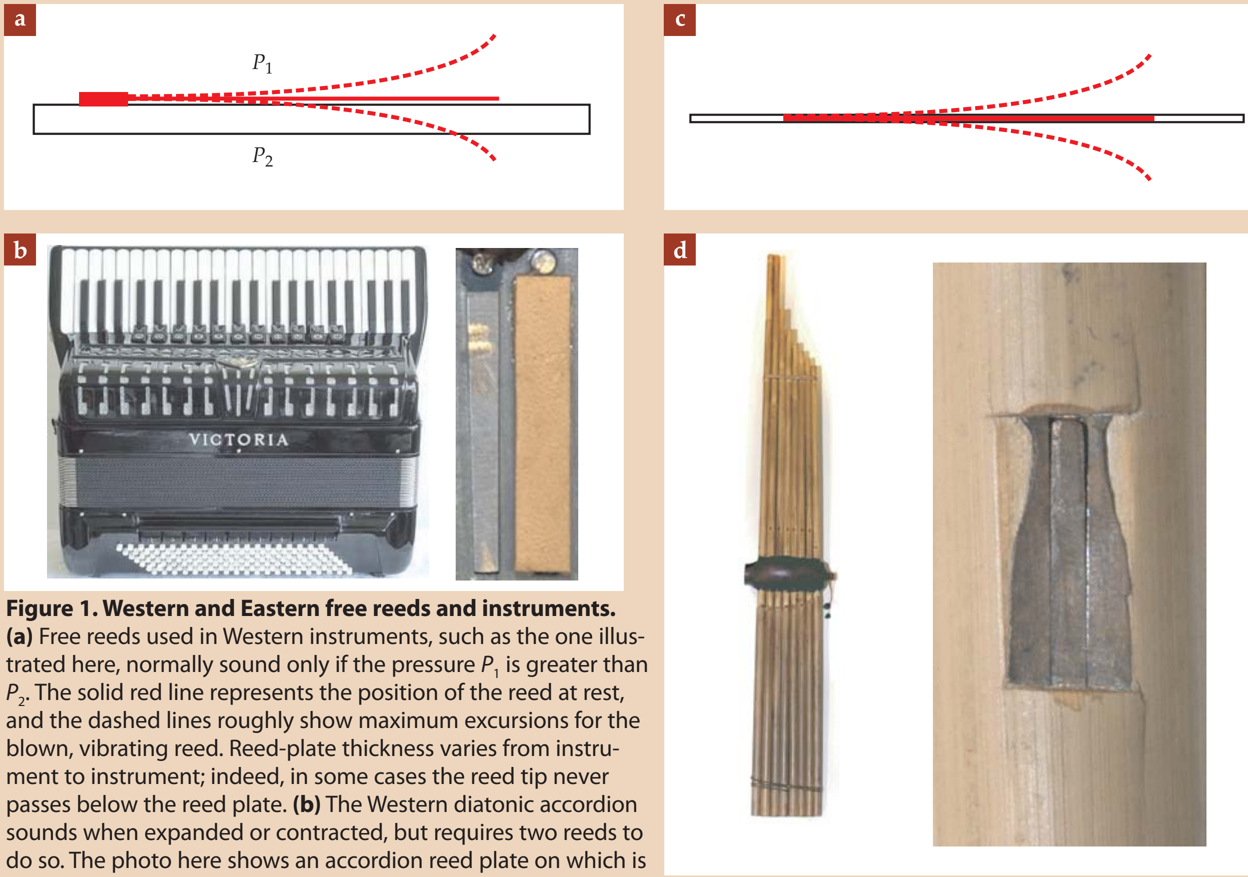


**Figure 1. Western and Eastern free reeds and instruments.** **(a)** Free reeds used in Western instruments, such as the one illustrated here, normally sound only if the pressure $P_1$ is greater than $P_2$. The solid red line represents the position of the reed at rest, and the dashed lines roughly show maximum excursions for the blown, vibrating reed. Reed-plate thickness varies from instrument to instrument; indeed, in some cases the reed tip never passes below the reed plate. **(b)** The Western diatonic accordion sounds when expanded or contracted, but requires two reeds to do so. The photo here shows an accordion reed plate on which is mounted a pair of reeds, one on each side of the plate. The reed that is visible sounds when air flows as if straight into the page; the leather valve prevents the flow from exciting the reed on the other side of the plate. The bright spots near the base and tip of the reed tongue reveal where material was scraped off to tune the reed. Note that the accordion's free reeds produce a full sound without the need for a pipe resonator. (Accordion photo by Henry Doktorski.) **(c)** In Asian free-reed instruments, the reed tongue is cut from the reed-plate material. The reeds are usually mounted in a pipe and often sound on both directions of air flow—that is, when the musician either blows air through the instrument or draws air from it. **(d)** Shown here are the Southeast Asian *khaen* and, enlarged, a khaen reed in a bamboo pipe. Each reed pipe in the khaen sounds on both directions of airflow.

constructed tongue is mounted outside the reed plate or frame in such a way that the reed only sounds with one direction of airflow. Normally such a reed behaves like a so-called blown-closed reed—that is, a reed for which a musician's initial attack tends to decrease the distance between the reed and the frame. A clarinet reed mounted in its mouthpiece is an example of a blown-closed beating reed. Several theorists have developed models for the oscillation of the air-driven free reed,[2–6] and the Western instruments have been subject to a number of experimental studies.[4–9] For example, as will be discussed further below, musical acousticians have learned that the sounding frequency of the blown reed is somewhat below the natural vibrating frequency of the reed tongue.

The Asian instruments, on the other hand, employ free reeds in which tongue and frame are cut from a single piece of material. Nowadays, metal is the usual choice, but other possibilities include bamboo or similar plant material. The reed tongue is positioned so that absent any pressure difference, it is in the closed position. Any initial pressure difference on the two sides of the reed will cause the reed opening to increase. Hence, reeds in Asian instruments are the blown-open type. In many instruments, including the khaen shown in figure 1d, a single reed functions with both directions of airflow. Because of their structure, the Eastern reeds must generally be coupled to a resonator, usually a pipe. For some very simple single-reed instruments, however, the player's vocal tract serves as a resonator. Theory predicts and experiment verifies that for the Eastern instruments, the sounding frequency of the reed–pipe combination is greater than both the natural frequency of the reed and the resonance frequency of the pipe.[4,8]

## Siren song

At a simple level of analysis, the sound production of a free reed is similar to that of a siren. As noted by Hermann von Helmholtz, "The passage for the air being alternately closed and opened, its stream is separated into a series of individual pulses. This is effected on the siren . . . by means of a rotating disc pierced with holes."[10] For the free-reed instrument, the air stream is interrupted by the oscillating reed tongue.

When a free-reed instrument is played, it's reasonably common for the tip of the reed tongue to oscillate about its equilibrium position with an amplitude of 15% of the tongue length. Furthermore, the design of the free reed ensures that when the tongue moves outside its reed plate, it presents a large opening. Thus, if the reed is oscillating due to a pressure difference between its two sides, the average volume airflow

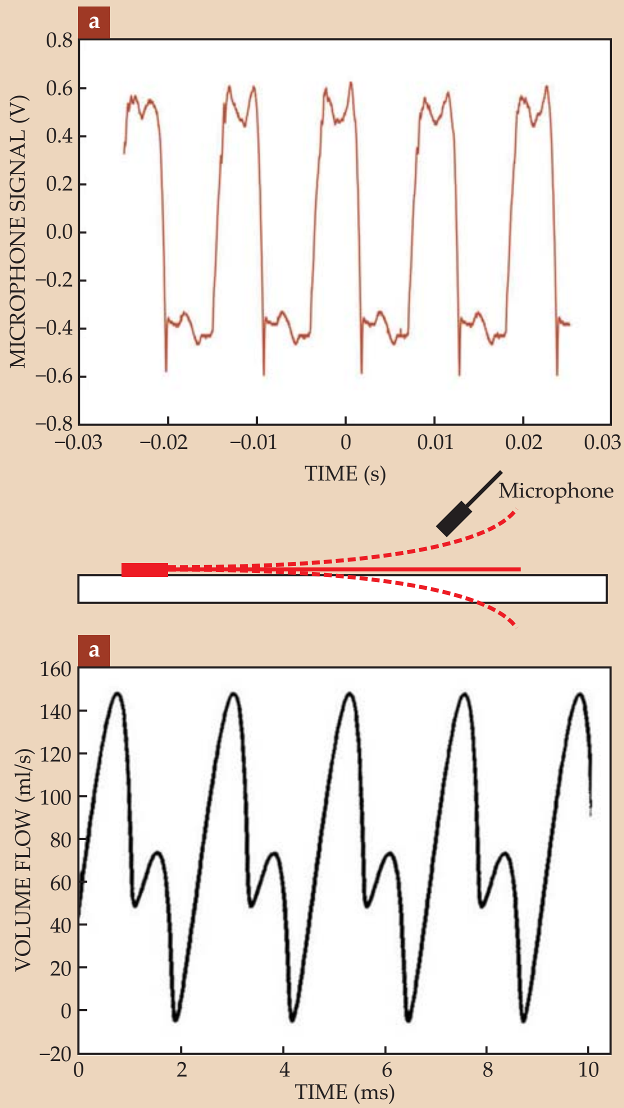


**Figure 2. Siren-like waveforms. (a)** The plot shows a pressure waveform from an accordion reed blown in a laboratory wind chamber. The approximate square wave is similar to that obtained from a siren. The schematic shows the reed and the position of the microphone that captured the pressure wave. Note that the reed travels a relatively small distance below the bottom of the reed plate. That asymmetry is reflected the microphone-signal amplitudes and in **(b)**, a plot of airflow rate as calculated by Laurent Millot for a reed similar to the accordion reed.[2] One complete cycle of oscillation results in two puffs of air. The smaller puffs correspond to the reed passing below the plate.

rate through the instrument will be large. Indeed, the rate has been measured for various instruments and calculated in theoretical models. For example, for a harmonica chamber housing a relatively small reed, the average flow rate is typically hundreds of milliliters per second, comparable to that for a clarinet.

The time-dependent, instantaneous volume airflow is not easy to measure, but investigators have made indirect measurements based on measured pressure variations. Theoretical calculations agree qualitatively with those measurements. Given the simplifying approximations made in the measurements and the theory, qualitative agreement may be the best one could hope for. Figure 2 shows the pressure waveform as measured by a microphone close to an accordion reed and compares it with the volume airflow of a similar reed as calculated by Laurent Millot.[2] As expected, the airflow rate occurs in two puffs per cycle, each puff corresponding to the reed opening on one or the other side of the reed plate.

A note played on the accordion or harmonica has an easily identified tone quality. An objective way to characterize it is to observe that the sound spectrum has abundant higher harmonics, as the approximate square waveform would suggest. Some listeners would describe the tone as rich, others would call it harsh; the choice depends on context and individual taste. In any event, the sound quality can be modified by the presence of a resonator.

## Resonators

As in all reed wind instruments, the frequency of vibration in a free-reed instrument is determined by both the reed and any resonators that are coupled to it. For the majority of wind instruments, including the Asian free-reed mouth organs, the primary resonator is a pipe. Indeed, in such instruments, the coupling between the vibrating reed and the air column of the pipe is necessary if the reed oscillation is to be stable. Several investigators, notably Jonas Braasch and Christian Ahrens, have measured sound production in Western free-reed organ pipes.[11] In that case, the reed pipe, which has a blown-closed free reed mounted within it, sounds at a frequency close to but slightly below the measured resonance frequency of the pipe. Recall, though, that in most cases the blown-closed free reeds of Western instruments operate without resonators.

The reeds in the Eastern mouth organs are blown-open reeds. For those instruments, the sounding frequency of the reed pipe is close to and slightly above the pipe resonance frequency.[8] The slightly raised sounding frequency has been measured in the Chinese *bawu*. As shown in figure 3, shortening the effective length of the bawu's pipe by opening tone holes not only raises the pitch but also results in a change in tone quality; that tonal change is similar to what occurs over the pitch range of a clarinet, but it is more dramatic and over a smaller range.

Typically, the range over which a reed–pipe combination can be made to sound in an instrument such as the bawu is less than an octave. The multiple pipe instruments, such as the khaen, sheng, and sho, function somewhat like miniature pipe organs, sounding a single note per pipe. Their construction permits a musician to play multiple notes at a time and take advantage of a wider range in pitch. The effective length of each pipe is tuned by cutting a large tuning slot, usually on the hidden side of the pipe. As a result, the longest pipes do not always play the lowest notes.

The physics of reed wind instruments is nonlinear. Nonetheless, a linear model for them formulated by Fletcher yields some key characteristics of how an air-driven free reed behaves.[12] In that model, the reed is taken to be a damped, driven harmonic oscillator coupled to a pipe resonator. Fletcher obtained from his model an expression for the complex acoustic admittance (volume flow divided by pressure) and found that self-sustained oscillation of the reed requires that the real part of the admittance be negative. My research group applied Fletcher's model to harmonium-type reeds from American reed organs to explore sounding frequency as a function of blowing pressure. We chose that type of reed because a number of laboratory measurements had been

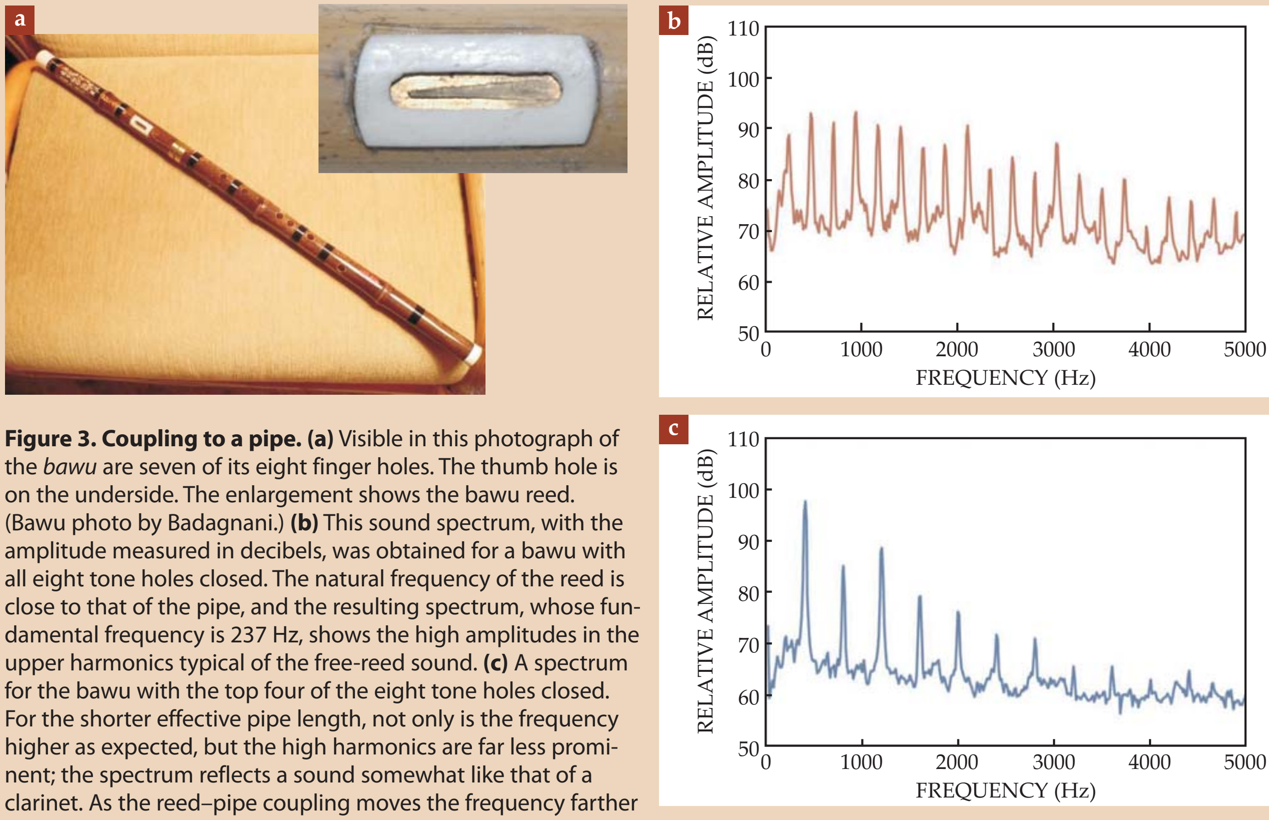


**Figure 3. Coupling to a pipe. (a)** Visible in this photograph of the *bawu* are seven of its eight finger holes. The thumb hole is on the underside. The enlargement shows the bawu reed. (Bawu photo by Badagnani.) **(b)** This sound spectrum, with the amplitude measured in decibels, was obtained for a bawu with all eight tone holes closed. The natural frequency of the reed is close to that of the pipe, and the resulting spectrum, whose fundamental frequency is 237 Hz, shows the high amplitudes in the upper harmonics typical of the free-reed sound. **(c)** A spectrum for the bawu with the top four of the eight tone holes closed. For the shorter effective pipe length, not only is the frequency higher as expected, but the high harmonics are far less prominent; the spectrum reflects a sound somewhat like that of a clarinet. As the reed–pipe coupling moves the frequency farther from the natural frequency of the reed, the tone quality is increasingly determined by the resonant frequencies of the pipe.

made, against which we could compare our theory.[9] Later Eric Dieckman and I used the Fletcher model to determine the sounding frequency of the free-reed pipes in Asian mouth organs.[8] Robert Johnston had previously used the model in his pioneering paper on pitch bending in the harmonica.[7]

The air-driven free reed is, of course, a more involved system than a simple harmonic oscillator; one complication is that the airflow and the sound field are three-dimensional. Several researchers have formulated more complete models of free-reed vibration, often in conjunction with experimental work on a particular instrument such as the accordion,[5] the harmonium,[3,6] or the sho.[4] Millot and colleagues, in addition to publishing significant experimental results for the harmonica,[13] have also formulated an ambitious and detailed model of free-reed oscillation.[2]

Pipes are not the only resonators involved in sound production by wind instruments. Resonators such as wind chambers can also be important. Reed chambers can affect both the pitch (though usually slightly) and the tone quality of sound. Some of the effects may be coincidental—after all, some sort of reed chamber is necessary to hold the functioning instrument together—but sometimes reed-chamber geometry is intentionally adjusted to influence tone quality. The most significant resonator, though, is often the vocal tract of the musician, particularly when a harmonica is being played.

## Pitch bending

As a matter of standard practice, skilled harmonica players bend the pitch of their instrument; indeed, such tonal alterations are a requirement for certain musical styles. Pitch bending exploits the coupling of harmonica reeds to the vocal tract of the player. Also important is the coupling between the two reeds, one for each direction of airflow, that share a single reed chamber. Significant acoustical studies of pitch bending in the harmonica include early work by Johnston[7] and more recent work headed by Millot[13] and Henry Bahnson.[14] Figures 4a and 4b show the construction of a harmonica and how two reeds are affixed to each reed chamber.

When the harmonica is played with straightforward blowing or drawing, the primary sounding reed is a blown-closed one coupled to the resonator, that is, the vocal tract of the musician. Johnston's groundbreaking study considered the volume of the oral cavity and the coupling between the two reeds that share a common chamber. He found that he could account for two common observations: The notes that can be bent are those for which the primary reed sounds a note higher in frequency than that sounded by the secondary reed, and the notes can be bent downward to pitches between those sounded by the two reeds. Figure 4c shows how the amplitudes of the primary and secondary reeds evolve as a harmonica player executes a draw bend.

Unusually skilled players use what are called overblows and overdraws to bend notes beyond the frequencies of the chamber reeds. The technique involves more than just blowing or drawing much harder than usual. In particular, the configuration of the vocal tract, not just its volume, is an important and difficult-to-realize element. The Millot and Bahnson studies have addressed those advanced techniques.

Like the harmonica, the accordion has two reeds in each chamber. But unlike the harmonica, the accordion is mechanically blown and the reeds don't couple to the vocal tract of the player. It might therefore seem that pitch bending in an accordion is impossible or severely limited. In fact, a player of a standard accordion can bend the pitch downward with a combination of increased pressure from the bellows and re-

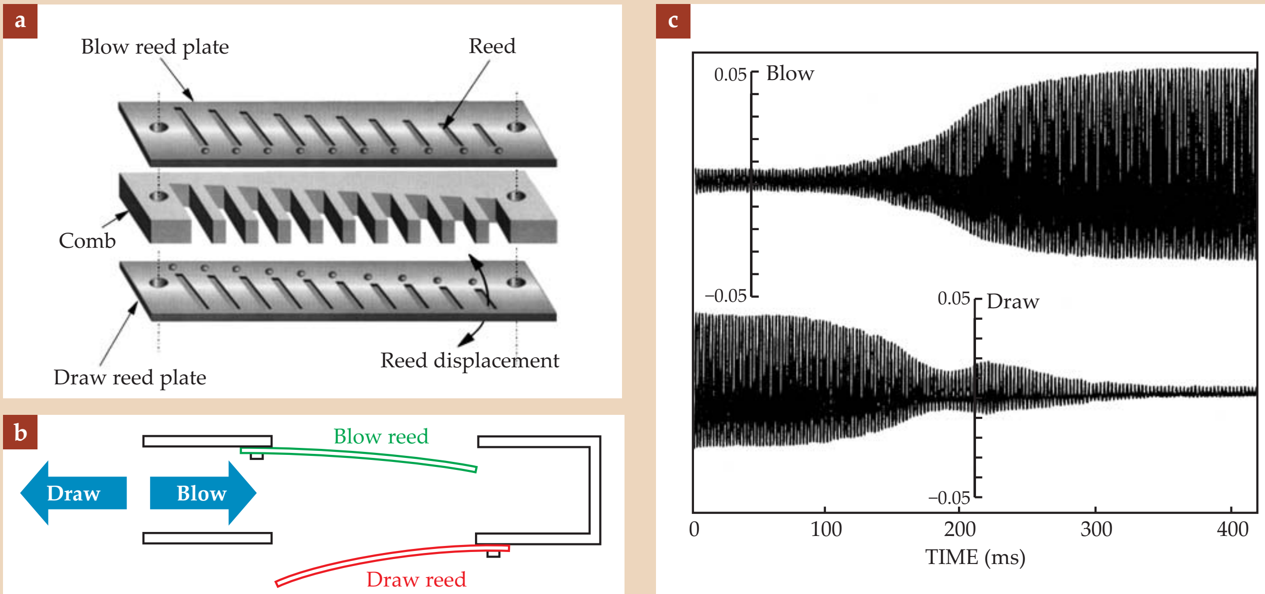


**Figure 4. Pitch bending in the harmonica. (a)** This exploded view of a 10-hole diatonic harmonica shows the reed plates and the separating comb, but not the covers of the reed plates. **(b)** Reeds are mounted on the inside surface of the blow reed plate and the outside surface of the draw reed plate. Blowing initially closes the blow reed into the blow plate (in the figure, the reed has since oscillated outside the plate) and opens the draw reed out of the draw reed plate. The reverse happens on drawing. Normally, the primary reed—the blow reed when the musician blows and the draw reed when the musician draws—is the most active and responsible for the pitch of the note. Nonetheless, the secondary reed always oscillates. **(c)** Although coupling to the vocal tract can be used to bend the pitch of a single reed, in the harmonica the bending involves coupling two reeds, and the motion of the secondary reed is significant. The plot here shows the relative displacement of blow and draw reeds as a player executes a draw bend from G to approximately F-sharp. The draw reed sounds initially, but the blow reed takes over as the player continues to draw but changes embouchure. (Panels a and c adapted from ref. 14. Panel b includes elements adapted from refs. 13 and 14.)

stricted airflow achieved by partially opening a pallet valve. Such pitch bending is occasionally called for by composers, and it may be a useful special effect. But it does not provide the kind of flexibility comparable to that at the disposal of a skilled harmonica player.

An alternate route to pitch bending on the accordion involves modifying the accordion to include an additional resonating pipe or chamber for each of the instrument's keys. Thomas Tonon has recently developed, patented, and implemented a practicable pitch-bending instrument that gives its player a flexibility similar to that available to a harmonica player.[15] By increasing the pressure on the key in the pitch-bending accordion, a musician can continuously bend the note downward about one semitone. The mechanism exploits the fact that a blown-closed free reed coupled to a pipe will sound at a frequency below the pipe resonance. In accordions, concertinas, and the like, each pair of reeds associated with a key is mounted over its own cavity. The cavity generally affects the timbre of the instrument, but it usually has little effect on the frequency of vibration of the reeds, since resonances between reed and cavity are rare. In the Tonon instrument, the cavity is intentionally designed to have nearly the same resonance frequency as the reeds; changing the key pressure enables a musician to vary the coupling of the reeds to the pipe.

Researchers continue to investigate the acoustics of free-reed instruments. Certainly, pitch bending and tone-quality control are topics of great interest to instrument makers, performers, and listeners. But acoustical research into those subjects depends on a deeper understanding of the fundamental properties of the swinging-door reeds and their couplings that together drive so many of the musical instruments of the world.

*The online version of this article includes a brief chronology of key events in the history of free-reed instruments.*

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