Free Reeds: An Intertwined Tale of Asian and Western Musical Instruments

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Introduction

Free reed instruments are a class of reed-based wind instruments where a reed swings freely through an open frame to generate a sound. The harmonica and the accordion are two popular free-reed instruments in the Western world, and the mouth organs sho (see youtu.be/yUpr1F1dZt0) and sheng are two prominent Asian examples (**Figure 1**). The free-reed mechanism provides a distinctive sound for musical instruments and demonstrates some extraordinary acoustic phenomena that are discussed in this article. Given that classical orchestras usually lack free-reed instruments, it is the wind instrument type that readers are probably least familiar with, even though they are widespread in traditional Asian music and popular Western music.

To understand free reeds in the larger context of wind instruments, one can look to the von Hornbostel and Sachs (1914) classification of musical instruments, which is still used today. For example, in terms of the article classification system used by *The Journal of the Acoustical Society of America*, von Hornbostel and Sachs primarily categorized instruments based on their tone generators, the part of the instruments that essentially produces the sound. The top categories in the classification system for music divide instruments into wind (aerophones), percussion, and strings. Wind instruments are then defined by their sound-generating mechanisms. Most wind instruments use the players' lungs to create an overpressure by blowing, whereas in a few instruments like the harmonica, a sound can also be created while inhaling (drawing), thus forming an underpressure reservoir.

Figure 1. *Examples of two popular free-reed instruments, the Chinese sheng (**left**) and the European accordion (**right**). Accordion image by Henry Doktorski, used under CC BY-SA 3.0 license.*

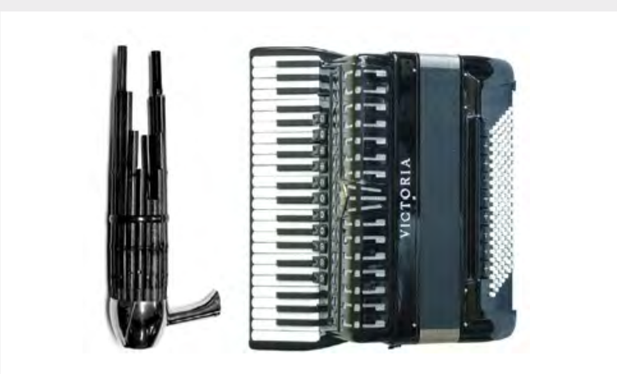

Figure 2 shows how reed and flute instruments evolved over time in these categories. All available evidence points to Southeast Asia as the region of genesis for musical free-reed instruments. Without a doubt, the invention of the earliest wind instruments was a combination of ease of build and a chance for discovery. Early wind instruments were often built from objects found at home, such as bird bones, animal horns, and hollow wood and reeds. Unfortunately, some materials are not well-preserved over time like others, so we know of bone flutes that are about 50,000 years old (Atema, 2014) and other early instruments from animal bones, but not of similar old instruments made, for example, from wood.

Unfortunately, the wood used to make the early prototypes of wooden free-reed instruments rotted in Southeast Asia's tropical climate, leaving some of the history up to conjecture. The feili of the ethnic Yi group in Yunnan, China, is one of the, if not the earliest, free-reed instruments (Lam, 2003/2004). It is a straw-made free-reed instrument with

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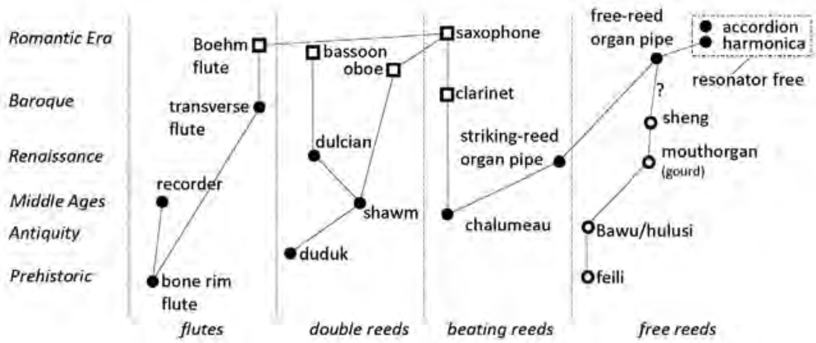


Figure 2. *Development of musical wind instruments over time for different music periods from Prehistoric to the Romantic Era. Instrument families are grouped according to the instrument classification type: flutes, double reeds, beating reeds, and free reeds (von Hornbostel and Sachs, 1914).* ***Solid lines:*** *evolutionary connections;* ***open boxes:*** *current orchestral instruments;* ***circles:*** *Asian free-reed instruments.* ***Question mark*** *indicates the still-debated question of whether European free reeds were copied from Asian free reeds.*

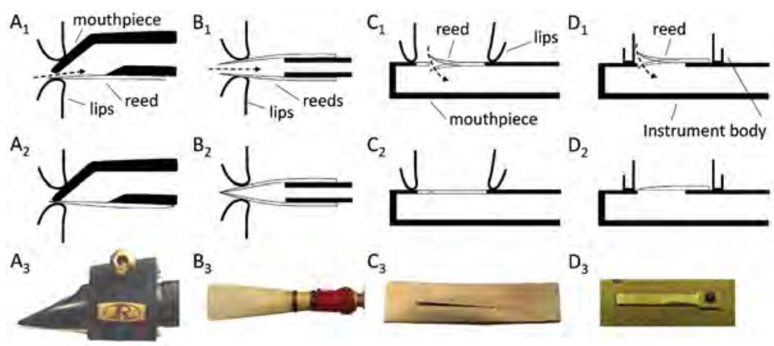


Figure 3. *Functional schematics (****side views****) and pictures of common reed mechanisms.* ***A_1:*** *striking reed mechanism of a saxophone mouthpiece. The reed acts as a periodically opening valve, and air will flow when it is open in the direction of the* ***dashed arrow****.* ***A_2:*** *airflow will stop when the reed is closed, and the periodically moving airflow will create the sound.* ***A_3:*** *actual saxophone mouthpiece (****side view****).* ***$B_{1\text{-}2}$:*** *periodic airflow for a double reed where two reeds vibrate against each other to enable and stop the airflow periodically.* ***B_3:*** *actual bassoon double reed (****top view****).* ***$C_{1\text{-}2}$:*** *airflow for an Asian free reed. In this case, the reed can swing freely through the frame.* ***C_1:*** *"open door" state, with each reed above the frame.* ***Dashed line:*** *alternative open state below the frame.* ***C_2:*** *"closed door" state.* ***C_3:*** *Asian bawu free reed (****top view****). In this example, the reed and the frame are made from the same metal piece and are simply separated by two narrow cuts.* ***$D_{1\text{-}2}$:*** *function of the European-type free reed that simply differs from the Asian-type free reed by mounting the reed above the frame and not within frame. It is mounted outside the reed plate or frame in such a way that the reed only sounds with one direction of airflow. In contrast, the Asian free reed is in plane with the frame (****$C_{1\text{-}3}$****).* ***D_3:*** *actual harmonica free reed that is riveted onto the frame. The reed is, therefore, slightly elevated from the frame.*

three finger holes that is very simple to make. An incision is made in the upper end to produce the free reed. In accordance with the Yi's oral tradition, a girl who was mute discovered the feili, and it became her voice. A sheng, a Chinese mouth organ with free reeds, is the earliest known example of a free-reed instrument, dating from 430 BC (von Falkenhausen, 1993).

Acoustics of Free Reeds

Free and Beating Reeds

Figure 3C shows that 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. It depicts the "open door" state, with each reed above the frame and the alternative open state below the frame, and the "closed door" state. Also shown is an Asian free reed. In this example, the reed and the frame are made from the same metal piece and are simply separated by two narrow cuts.

In contrast, **Figure 3A** shows that the mechanism of a beating (or striking) reed in an instrument such as the saxophone is slightly wider than the opening over which it is mounted. In double-reed instruments (**Figure 3B**), two reeds oscillate against each other, and the mechanism does not require a frame like beating- and free-reed instruments.

Asian and European Free Reeds

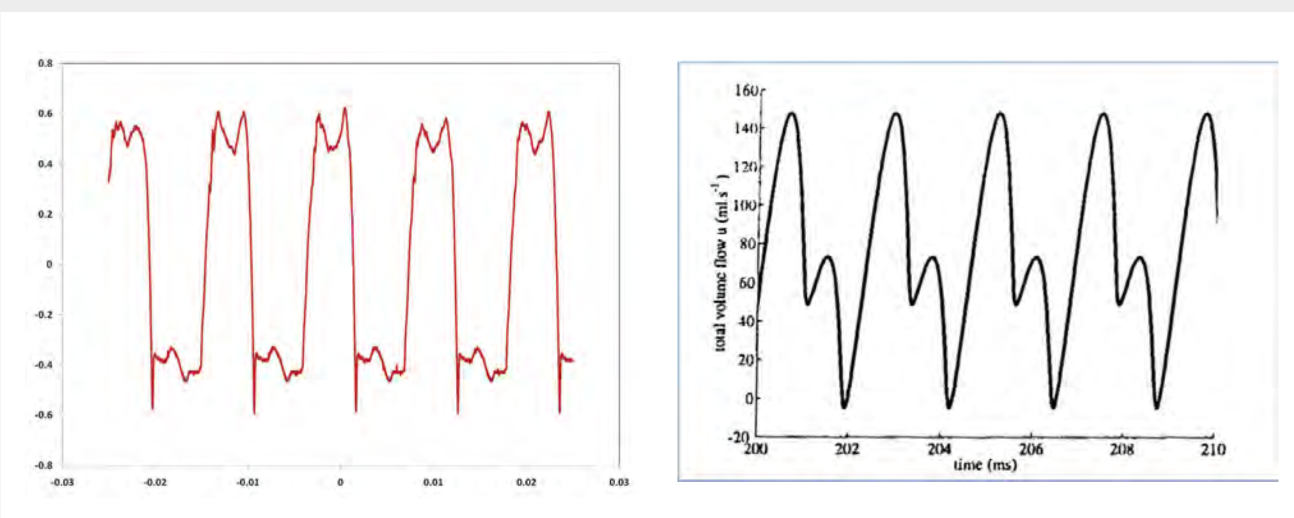
The principal acoustical difference between the Western and Asian free-reed instruments is in the design of the reeds (**Figure 3**). The Western instruments employ reeds that are separately constructed from the frame and mounted on top of the latter. The reed is, therefore, slightly elevated from the frame and is mounted outside the reed plate or frame in such a way that the reed only sounds with one direction of airflow (**Figure 3D**). In contrast, the Asian free reed is in plane with the frame (**Figure 3C**). This small constructional difference has very important acoustic consequences: The Western free reed can sound on its own, whereas the Asian free reed needs a resonator like a pipe to sound. We discuss this effect in **Asian Free Reeds**.

At a simple level of analysis, the sound production of a free reed is like that of a siren. As noted by Helmholtz (1954, p. 95), "The passage for the air being alternately closed and opened, its stream is separated into a series of individual pulses. This is affected on the siren…by means of a rotating disc pierced with holes." For the free-reed instrument, the airstream is interrupted by the oscillating reed tongue.

Normally, a reed of a Western wind instrument behaves like a so-called blown-closed reed, that is, a reed where 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 (e.g., St. Hilaire et al., 1971).

When a free-reed instrument is played, it is reasonably common for the tip of the reed to oscillate about its equilibrium position, with an amplitude of 15% of the reed length. Furthermore, the design of the free reed ensures that when the reed 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 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, which has a much larger reed.

Figure 4. ***Left:*** *relative pressure waveform of a blown accordion reed.* ***Right:*** *calculated airflow rate of the reed after Millot and Baumann (2007). Adapted from Cottingham (2011).*



Waveform of Free Reeds

Figure 4, *left*, shows the pressure waveform as measured by a microphone close to a blown accordion reed in a laboratory wind chamber. The waveform approximates a square wave similar to that of a siren. **Figure 4**, *right*, depicts the reed's volume airflow of a similar reed as calculated by Millot and Baumann (2007). As expected, the airflow rate occurs in two large puffs per cycle, each puff corresponding to the reed opening on one or the other side of the reed plate. The smaller puffs occur when the reed passes below the plate.

The von Hornbostel-Sachs classification (1914) further differentiates if musical instruments use a resonator that changes the pitch of the tone generator or if they are resonator free. All orchestral wind instruments use a resonator that can be effectively changed in length through finger holes (woodwind instruments), slides (trombones), or valves (for most brass instruments; see Moore, 2016) to change the pitch of the instrument to play melodies. Nearly all Western free-reed instruments like the harmonica and the accordion, however, are resonator free, so they must use a set of reeds, one for each tone (see **Figure 2**). In the Western free-reed design, a resonator will usually not affect the pitch of the reed by much, and instruments require a separate reed for each tone. In Western pipe organs (Angster et al., 2017) and in Asia, free-reed instruments with resonators are very common, for example, in the form of the bawu (see youtu.be/UG8D1zyqYFU) and hulusi (see youtu.be/pPvJa6TYjqU). Here, the dimensions of the resonator, the length in particular, determine the sounding fundamental frequency of the reed.

A note played on the accordion or harmonica has an easily identified tone quality. An objective way to characterize this one quality 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 the context and individual taste. In any event, the sound quality can be modified by the presence of a resonator.

Free Reed Characteristics

Free reeds have a characteristic sound that allows musicians to identify the free-reed instruments' sound as a distinct group (like an average person can clearly hear the different vowels /a/, /e/, /i/, /o/, and /u/). This means that

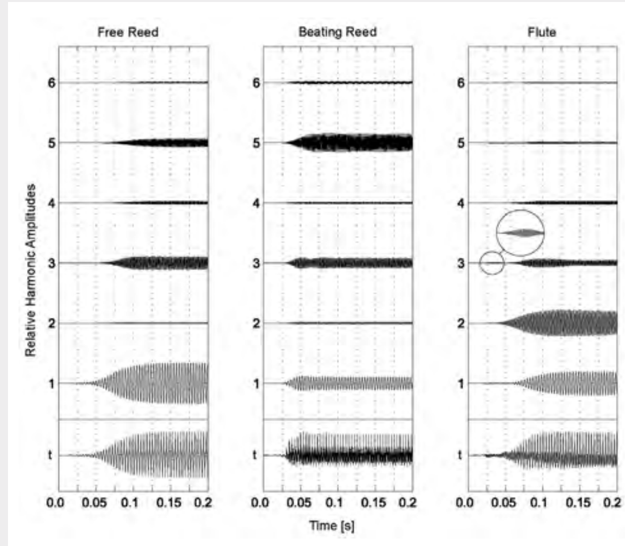


Figure 5. *Onset sounds of a free reed compared with a beating reed and flute. Each graph shows the total sound (**bottom**) and the first six partial tones with rising frequencies (**top**). The initial sound starts at the third partial tone, has a very low amplitude (**small circle**), and has been magnified to make it visible (**large circle**). Adapted from Braasch and Ahrens (1999).*

a trained musician hears a free-reed instrument out from beating or double-reed instruments just by the sound-producing mechanism (listen to an accordion sound example at youtu.be/CJFQTP2RXo4). Free reeds have a unique common onset behavior that can be used by the listener to perceptually separate the free-reed sound from other musical instruments (Braasch and Ahrens, 2000). Compared with a beating reed, the onset duration (the time needed to reach the full amplitude of a tone after its initial beginning) for a free reed is fairly long.

Moreover, the free-reed onset phase occurs with a delayed progression toward the higher harmonics, meaning that the fundamental frequency sounds first and then the higher harmonics start to appear with increasing frequency (**Figure 5**, *left*). The onset phase of beating reeds is usually much shorter, and all harmonics appear simultaneously because the reed starts to beat against the frame right away (**Figure 5**, *middle*).

Flutes can also have a long onset phase, but their sound typically starts as a noise signal produced by the jet stream formed against an edge that is then converted to a harmonic signal through the resonator. In the case shown **Figure 5**, *right*, the sound starts at the third partial tone. In addition to what can be seen in **Figure 5**, free reeds also have a unique upward shift in fundamental frequency during the onset phase, often in the ascending order of semitones that stretches over several dozen milliseconds. This sound effect gives free-reed instruments their characteristic sound in both Eastern and Western cultures.

Asian Free Reeds

Asian instruments employ free reeds in which the reed and its frame are cut from a single piece of material (**Figure 3C**). Nowadays, metal is the usual choice, but other possibilities include bamboo or similar plant material (Miller, 1981). 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 its opening to increase.

Hence, reeds in Asian instruments are the blown-open type. In many instruments, including the khaen, a single reed functions with both directions of airflow (see youtu.be/9_u5w5d2xiQ). Because of their structure, the Eastern reeds must generally be coupled to a resonator, usually a long round pipe with a constant diameter. For some very simple single-reed instruments, however, the player's vocal tract serves as a resonator. Theory predicts and experiments verify 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 (Hikichi et al., 2003).

Figure 6. *Asian free-reed instruments.* ***A:*** *bawu;* ***B:*** *hulusi;* ***C:*** *khaen;* ***D:*** *detail of reed found in each bamboo pipe element of the khaen. Each reed pipe in the khaen sounds when blown or drawn.*

Free Reeds with Resonators and Finger Holes

Many Asian free-reed instruments, such as the bawu (see youtu.be/UG8D1zyqYFU), use a cylindrical bamboo resonator with finger holes to change the pitch (see **Figure 6A** and **B)** in a way similar to the way the clarinet is played by pressing tone holes. The bawu is a diatonic musical instrument, which means it has only defined notes for one scale, for example, C major. Other scales can only be played with extraordinary finger combinations, like opening a finger hole halfway. In contrast, modern Western orchestral instruments use complex key or valve mechanisms, so that the instrument can be played throughout all musical keys with a similar balanced tone quality.

The construction of the bawu is unique because it combines a diatonic body with a free-reed generator. Although nearly every culture uses wind instruments in the form of flutes and double-reed and beating-reed instruments in conjunction with a diatonic resonator, but the use of a free reed with a diatonic resonator is unique to Southeast Asia. The hulusi is a similar instrument that has one or two additional reed-resonator systems to produce drone sounds to accompany melodies. For these instruments, it is typically not possible to oscillate the reed into an upper register, and the range is, therefore, limited to a major ninth.

However, in contrast to Western woodwind instruments that only produce additional notes above the fundamental register, the reed of the hulusi can be blown in a way that produces two additional sounds with frequencies below the natural register of the instrument.

Mouth Organs

Multipipe mouth organs are unique to Asia and exist in various forms used in folk and official court ensembles. For every offered pitch, the Asian mouth organ uses a distinct reed that is coupled to a resonator with a single finger hole (see **Figure 6C** and **D**; also **Figure 1**, *left*). Only when closing the finger hole of a pipe will the reed sound. This is because the open finger hole will cause an impedance mismatch that prevents the reed from oscillating; recall that the Asian free reeds are blown-open types and that these require a resonator to sound. Acoustically speaking, opening the finger holes takes the resonator away, and the reed can no longer sound.

Mouth organs were originally built around a gourd as the main body, but the modern sheng in China and sho in Japan consist of metal bodies with bamboo pipes. In general, mouth organs are polyphonic, producing harmonic clusters outside the Western major/minor chord tradition. The clusters can be varied dynamically to create complex textures because the free reeds are very stable with changing wind pressure.

Western Free Reeds

The exact origin of the Western free-reed type is still unclear, with two competing theories (which is why we placed the *question mark* in **Figure 2**). The first theory assumes that the Western free reed was copied from Asian instruments. Indeed, it has been documented that individual instruments were imported to Europe as curiosities, although there is no indication that they were played or that their mechanisms have been understood. The alternative theory assumes that Western free reeds were invented independently from their Asian counterpart. European free reeds are not only built in a uniquely different way from the Asian free reed, but the standard European free-reed construction is also more complicated.

The earliest known European free-reed instrument was a speaking machine by Christian Gottlieb Kratzenstein to produce vowel sounds. The device was based on musical instrument technologies of pipe organs and won him a prize in 1780. In his elaborate treatise, Kratzenstein does not mention the Asian free reed with a single word, even though there is speculation he might have seen an Asian mouth organ in Copenhagen, Denmark. Instead, Kratzenstein argues that he redesigned the striking reed of an organ to swing freely through the frame to avoid the harshness that is found for a striking reed when hitting the frame every cycle, a sound very uncharacteristic of the human voice (Ahrens and Braasch, 2003). One needs to keep in mind, though, that science at the time was a European-centric endeavor, and it might have been then considered ethical to omit naming outside sources.

Free-Reed Pipe Organ Stops, Physharmonica, and Reed Organs

The first musical European free-reed instruments were organ pipes that evolved shortly after Kratzenstein's invention (for a general acoustical introduction to pipe organs, see Angster et al., 2017). Free-reed organ pipes soon reached their final form when the tuning mechanism was added (Strohmann, 1811). Early on, free-reed pipe organ stops became popular in Germany, France, and other central European countries.

One of the earliest successful freed-reed instruments in Europe was the physharmonica (see en.wikipedia.org/wiki/Physharmonica), an instrument without resonators. These instruments existed before free reeds were manufactured industrially and were an early attempt to build expressive pipe organs. By quickly changing wind pressure through a foot-controlled pressure-variable bellow system, they can be played quieter or louder. In this context, it is important that only free reeds maintain their pitch under wind pressure variation. In contrast, traditional flute and striking reed stops demonstrate an audible increase in pitch with increasing wind pressure, an effect also experienced by students when learning the recorder. The success of the physharmonica was rather short-lived after it became apparent that the tuning stability was a real problem because the frequency-stable reeds detuned relative to the widely common flute and striking-reed pipes with the changing temperature in churches.

The reed organ, the harmonica, and the accordion all evolved from the physharmonica, and the latter two instruments are still the most frequently used free-reed instruments in the Western world. Although the basic acoustical principles of operation apply to all three, they differ in the design of the air supply. The reed organ uses a keyboard-operated set (or sets) of reeds, all sounding on the same direction of airflow (Cottingham, 2002). This is affected by mounting the reeds on a suitable wind chest. This can be done with either an overpressure in the chest (a "pressure" instrument) or an underpressure (a "suction" instrument). The accordion family of instruments uses a hand-operated bellow that provides airflow in either direction through the reed chambers and hence requires a separate reed for each direction of airflow. The modern mouth-blown harmonica also uses two reeds in each wind chamber.

Harmonica

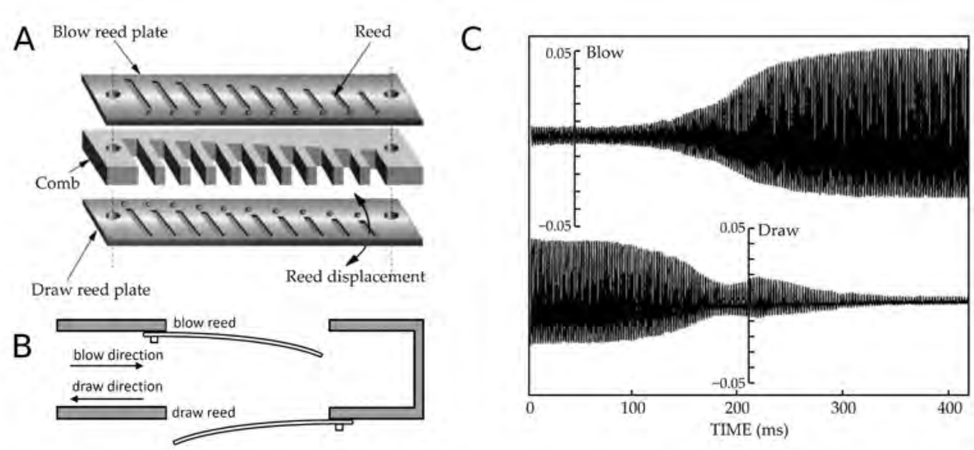
The harmonica is arguably the simplest European free-reed instrument, but its design provides unique, complex acoustic features that are discussed at the end of this section. The comb-shaped frame of the harmonica contains chambers with free reeds, covered by top and bottom plates that can be blown directly using the lips (and tongue) to channel the air to the desired slot or group of slots for playing single tones and chords (see **Figure 7A**). The exact course of invention remains unclear, although the first prototype appeared sometime in the first quarter of the nineteenth century.

Joseph Richter invented the current diatonic harmonica design around 1825. His harmonicas have two reeds per slot, where one is activated by blowing and the other by drawing air (see **Figure 7B**). When blowing the harmonica, the blow reed closes initially inside the blow plate while opening the draw-reed plate. The blow reed then oscillates inside and outside the plate. **Figure 7** shows a snapshot of the inside state. It is more active than the draw reed and determines the pitch of the sound, but the latter is moving as well. The opposite effect occurs when drawing air. Then the draw reed has the primary motion. Adjacent blown reeds are tuned in thirds, and the corresponding drawn reeds are a (semi)tone off according to a diatonic scale. Diatonic harmonicas, which have 7 tones in each octave (2:1 frequency ratio) can be played chromatically by tone-bending individual reeds to complete all 12 tone steps in an octave like on a piano keyboard. Tone bending is an extended technique mastered by Howard Levy and others (see youtu.be/Pz2jPAxUuss).

Free reeds soon lent themselves for industrial mass production, making instruments cheaply available during the middle of the nineteenth century and leading to a popularization, especially in the amateur world. Already in 1827, the Austrian Chamber of Commerce reported 500,000 sold instruments in Vienna alone.

When playing the harmonica with straight blowing or drawing, the principal sounding reed is a blown-closed one coupled to the musician's vocal tract, which acts as a resonator. Johnston's (1987) groundbreaking research looked at the volume of the mouth cavity as well as the connection between the two reeds that share a chamber. He made two important observations. First, the notes that can be bent are those for which the primary reed plays a note higher in frequency than the secondary reed. Second, these notes can be bent downward to pitches between the two reeds. **Figure 7C** depicts the evolution of the amplitudes of the primary and secondary reeds when

Figure 7. ***A:*** *enlarged view schematic of a 10-hole diatonic harmonica with reed plates and comb that isolate the reed pairs into the chamber. The two-reed plate covers that are below the top and bottom of the reed plates are not shown.* ***B:*** *functional side view of the harmonica.* ***C:*** *relative acoustical sound pressure measurement of the harmonica pitch-bending effect. Adapted from Bahnson et al. (1998).*



a harmonica player performs a draw bend. When the player draws air, the depicted draw reed starts to sound in G. By adjusting the shape of the vocal tract and tongue position after the sound has started (while continuing drawing), the blow reed in F-sharp takes over and the sounding pitch increases. This effect is called a draw bend.

Skilled players can further extend the pitch-bending range through overblowing and overdrawing to sound the harmonica beyond the frequencies of the chamber reeds by shaping their vocal tract. In this case, only one reed is used primarily. The technique entails more than just blowing or drawing more forcefully than normal. Bahnson et al. (1998) were able to show that the shape of the vocal tract, rather than its volume, enables this technique.

Accordion

An early accordion prototype was patented by Cyrill Demian together with his sons Karl and Guido in 1829, giving the instrument its name. Demian's instrument had buttons to activate free reeds for one hand only while the other hand operated the bellow for the wind supply. Nowadays, both hands operate buttons or keys to play bass and treble sounds at the same time. Demian used two reeds for each key, mounted in opposite directions. Like the harmonica, one reed sounded when the bellow is squeezed, and the other when the bellow is drawn. This feature is unique to European free-reed instruments, given the instrument's characteristic sound of chord progression in popular music.

Today's accordions commonly use the right hand for the treble keys or buttons and the left-hand buttons for the bass and chords. Because keyed free-reed instruments do not have a dynamic key system like the piano, the bellows operation is a crucial part of dynamics and expression, using the benefit of the tuning stability of free reeds with changing wind pressures that were already key for expression devices in pipe organs.

Recent Developments

Although most known free-reed instruments matured into their final design decades ago, several new instrument developments with free reeds have been conceived. Missin (2011) reports a key mechanism to extend the tonal range of the bawu by Li Song (see patmissin.com/history/bawu.html). Tonon (1998) invented and patented an accordion in which the player can simulate the ability of the harmonica player to bend pitches. In his accordion construction, he can lower the pitch of a note by gradually coupling the reed to an interior pipe resonator.

Finally, Braasch (2019) retrofitted a soprano saxophone with numerous tone generators, including an enlarged bawu reed providing a similar tonal range to the original bawu. This way, the saxophone can be played in the lower register without the need to control the lip muscles. It becomes very easy to play for beginners who have not trained their lip muscles yet. The effect of how different tone generators sound with the same saxophone resonator can be heard at youtu.be/hz8jsEN4QjA.

Concluding Remarks

Soon after their (re)invention, free reeds became the sound generators of choice for inexpensive and even toy-like musical instruments in the West and then the whole world. Industrial manufacturing techniques allowed the mass fabrication of harmonicas, accordions, and reed organs. The association of the characteristic free-reed sound with these popular musical instruments became a challenge for free-reed instruments for classical music, like the reed organ and free-reed pipe organ stops. The mass fabrication of free-reed instruments declined rapidly after the invention of the transistor and integrated circuits because they allowed even cheaper mass-produced instruments. Free-reed instruments prevailed wherever their characteristic sound or expressive possibilities were sought, for example, the blues harmonica, the Tango bandoneon, and the mellow bawu tone for traditional Chinese music.

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