Cooperative behavior of both reeds in the channel of a blues harmonica when bending

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Blow and draw reed in a channel

There are two reeds in each channel of a blues harmonica, one of which (the blow reed) is mounted on the inside and the other (the draw reed) on the outside (see Fig. 1). The reeds can oscillate through openings in the reedplate (free reeds). When the harp is blown lightly (before the vibration starts), the blow reed is pressed towards the reedplate and thus closes the opening in the reedplate a little more. The draw reed, on the other hand, is pushed away from the reedplate during blowing, thereby enlarging the opening. It is said that the blowing reed acts as a closing reed when blowing and the drawing reed as an opening reed. The opposite is true for drawing: the draw reed is the closing reed and the blow reed is the opening reed.

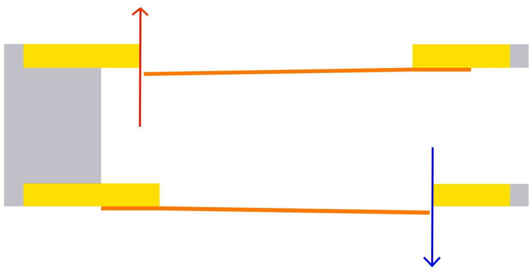

Figure 1: Section through a blues harmonica (scale drawing for channel #4 of a HOHNER Special 20 in C). Yellow: reedplates. Orange: reeds. Above: blow reed, below: draw reed. The arrows indicate the axis directions for the respective oscillator equations.

Blowing or drawing with a relaxed embouchure produces normal blow or draw notes which are tuned just below the natural frequency of the blowing or drawing reed. The closing reed and the air through vocal tract and instrument perform powerful, self-excited oscillations, while the opening reed remains passive and is forced to vibrate with a small amplitude.

By changing the geometry of the vocal tract appropriately, notes can be created between the pitches of the normal notes in the channel. On the lower channels #1 to #6, the normal draw note sounds higher than the normal blow note and can be continuously "bent" downwards. The lowest possible drawbend is just above the frequency of the normal blow note in the channel. The normal blow note sounds higher on the higher channels #7 to #10, where blow bends are possible. In the following, we will focus on the lower channels, which are more important for playing practice. The lower a drawbend, the less the draw reed vibrates and the more the blow reed vibrates. It seems plausible that both reeds are actively involved in creating the self-excited oscillation of the overall system of reeds and air.

Transient behavior of a drawbend on the blues harmonica

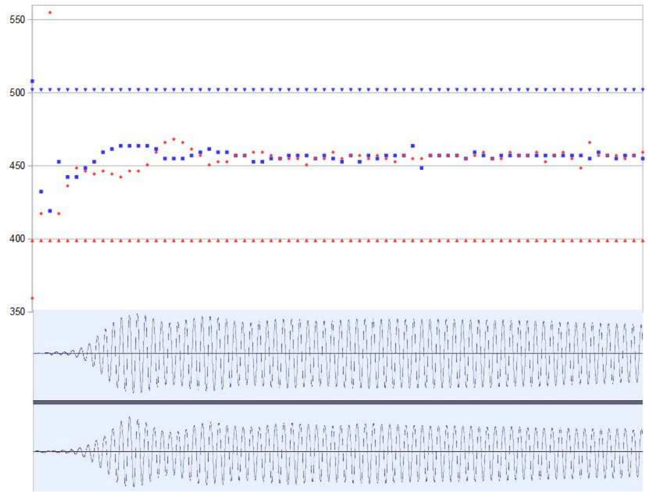

Figure 2: Pseudo-frequencies and reed movements during the transient response of a half-note bend on channel #3 of a C harp. Pseudo-frequencies (blue: draw reed, red: blow reed, horizontal rows: the respective natural frequencies) and wave forms (linear representation, top: draw reed, bottom: blow reed) as a function of time (ELX, Audacity open source).

Fig. 2 shows the transient response for a semi-note bending on channel #3 of a C harp. The movements of the draw reed (upper wave) and blow reed (lower wave) were recorded using an ELX (a kind of "pickup" for the blues harp based on optical sensors). Pseudo-frequencies were assigned to the reed movements by evaluating the wave files through reading the length of sample intervals (see Fig. 4). Fig. 3 shows one further example of pseudo-frequencies during transient oscillation.

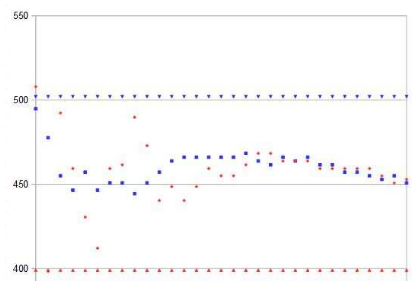

Figure 3: One further example of pseudo-frequencies during the transient response of a half-note bend on channel #3 of a C harp (cf. Fig. 2).

In Figures 2 and 3, the values for the draw reed are shown in blue and the values for the blow reed in red. The horizontal blue and red rows represent the natural frequencies of the two reeds. You can see how, during the transient oscillation process, the rather random movements of both reeds very quickly change into sinusoidal oscillations, whose frequencies, however, first have to align.

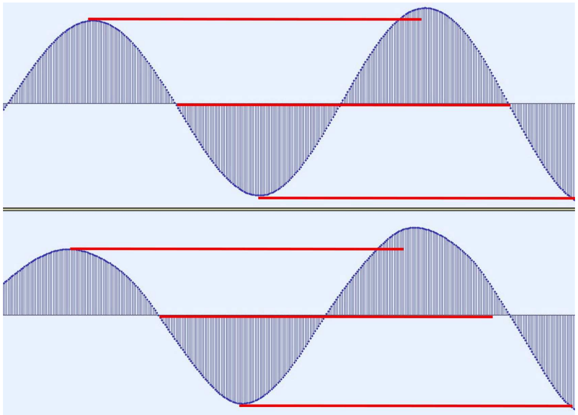

Figure 4: Reading the sample intervals (the vertical lines correspond to individual samples at 96000 samples per second). the distance between the zeros after two neighbouring maxima has been read for the draw reed (top). The distance (red) between the zeros has been copied to different places in the figure. The distance between zeros obviously also reflects the distance between neighbouring maxima or minima for the draw reed and is therefore a useful measure of the oscillation's pseudo-period. It is different form the corresponding distances for the blow reed (bottom). For the section shown, this results in a pseudo-frequency of 464Hz for the draw reed and 442Hz for the blow reed.

In [1], bending on the blues harmonica is explained in analogy to tone production on the clarinet or saxophone [2]. From today's perspective, a linear stability analysis is carried out in frequency domain [3]. Doing so, it is assumed a priori and without further justification that both reeds perform "infinitesimal" sinusoidal movements of equal frequency from the very outset. In view of Figures 2 and 3, this approach makes little sense.

Two closing reeds in the channel

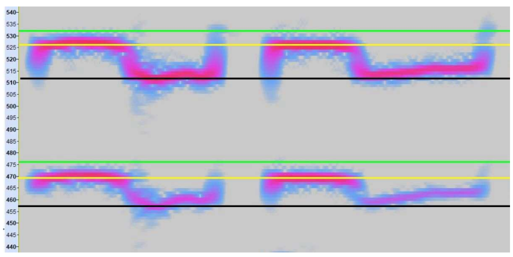

Figure 5: The fundamental frequencies of a sound recording as a function of time for bending with two closing reeds in channel #4 of a Bb harp (green: natural frequencies of the reeds, yellow: normal draw notes, black: drawbends, frequency analysis with Audacity open source).

For Fig. 5, the reed in channel #4 of a Bb harp that opens when playing a draw note was replaced by a closing reed of the same natural frequency. Part of the frequency analysis of the sound emitted to the outside for a draw bend is shown. Two normal playing frequencies (yellow) can be heard simultaneously below the natural frequencies (green) of the two reeds, both of which are then bent downwards (black). During bending, two closing reeds in the channel together with the common volume of air produce self-excited oscillations with clearly different, well-defined frequencies. It is therefore not the spatial proximity or the interaction with the same resonator that is decisive for the occurrence of a common playing frequency. Rather, bending on the blues harp is based on the fact that there is an opening and a closing reed in the channel, with the closing reed having the higher natural frequency.

Cooperative behavior of a closing and an opening reed during bending

Measurements in the steady state show that both reeds in the channel oscillate sinusoidally and at the same frequency [4] [5]. The figures 2 and 3 suggest that a stochastic process takes place during the transient process with this common frequency as a kind of "attractor". What is so attractive about a common oscillation frequency when a closing and an opening reed in the canal interact with the vibrating air in the channel and in the vocal tract?

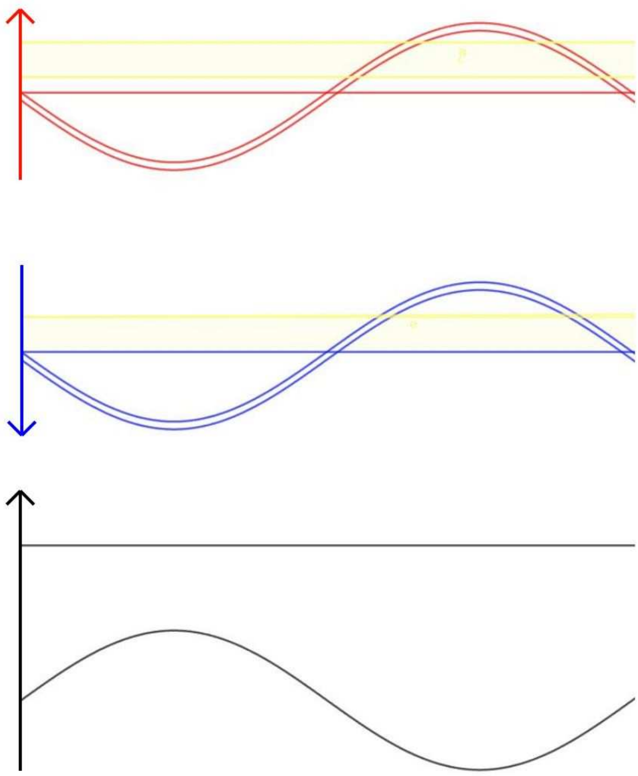

Figure 6: Oscillations of the reed tips (true to scale for a half tone bend on channel #4 of a C harp, see appendix) and fundamental oscillation of the air pressure inside the channel (qualitative). Top (red) blow reed, middle (blue) draw reed, bottom (black) pressure. The reed plates are shown in yellow.

Blues harmonica reeds oscillate freely through the openings in the reedplate, the movement of the tip of a reed can therefore be modelled by a 1-point oscillator equation with effective values of the parameters [4]. The oscillator equation and the resulting quantitative justifications for the following more qualitative discussion can be found in the appendix.

Fig. 6 visualizes the “attractor” when bending: (nearly) synchronous movements of the two reeds together with sinusoidal pressure fluctuations in the channel. We will explain how the figure fits the oscillator equations and furthermore illustrates the cooperative influence of the two reeds on the occurrence of self-excited oscillations.

Why sinusoidal pressure fluctuations? The reason is, that weakly damped reeds in the relevant frequency range of some hundred Hertz “feel” mainly the fundamental of the actual pressure oscillations in the channel. Blues harp reeds oscillate for a very long time (approx. one second, time enough for several hundred oscillations) when they are plucked. This shows that they are very weakly damped oscillators. For a halftone bend on channel #4 of a C harp, for example, the first harmonic in the pressure only causes about 4% of the amplitude generated by the fundamental oscillation.

Next we will fix the direction of the elongation axes. Careful blowing or drawing moves both reeds quasi-statically outwards or inwards. In order for this behavior to be reproduced by the oscillator equation (1), the axes for the elongations must both point outwards from the chamber as indicated in Fig. 1 and 6.

Given sinusoidal pressure fluctuations with frequency in the bending range, the oscillator equation predicts sinusoidal elongations which are nearly in phase for a reed with natural frequency above playing frequency and nearly opposed in phase for a reed with natural frequency below playing frequency. Thus, the elongations of the draw reed (blue curve in Fig. 6) will be in phase with pressure, the elongations of the blow reed (red) will be opposed. Considering the axis direction of the draw reed, this means that both reeds move synchronously.

Now the crucial difference emerges as to whether there is one opening and one closing reed in the channel or whether there are two closing (or two opening) reeds. Self-excited oscillations of the overall system of the two reeds and the air are created by mutual influence. Air pressure causes forces acting on the reeds, and reed motions influence air pressure by closing and opening the slits between reeds and reedplates. Decisive is now the position of the reedplates relative to the reeds (see Fig. 6, the reedplates are marked in yellow). (Only) for one opening and one closing reed, synchronous motion means synchronously opening and closing the slits. It is this cooperative impact on pressure that might be optimal for the generation of self-excited oscillations with common frequency.

Summary and outlook

Simply looking at the oscillator equations makes it clear why a common oscillation frequency of the two reeds in the channel of a blues harmonica represents a kind of "attractor" for the steady state of a drawbend. An opening and a closing reed are able to synchronize their influence on the pressure fluctuations in the channel. What is not explained is how both reeds very quickly agree on this common frequency. And of course, it should also be clarified what determines the playing frequency. The resonance characteristics of the vocal tract certainly play a decisive role. However, data on the resonance behavior of the vocal tract while playing the blues harp are still lacking [3].

Appendix

Figures 1 and 6 are based on own measurements on channel #4 of a HOHNER Special 20 MARINE BAND in C. Both reedplates are $0.9mm$ thick, approximated values for reed thickness and clearance gap are listed in table 1.

Table 1: Parameters for the reeds system

	blow reed	draw reed
effective reed area S	$1.1\ 10^{-5} m^2$	$1.1\ 10^{-5} m^2$
reed thickness	$2\ 10^{-4} m$	$2\ 10^{-4} m$
clearance gap	$-\ 2\ 10^{-4} m$	$2\ 10^{-4} m$
natural frequency ω_0	$3300 s^{-1}$	$3700 s^{-1}$
damping constant $2r$	$16 s^{-1}$	$16 s^{-1}$
effective mass m	$3.9\ 10^{-6} kg$	$3.1\ 10^{-6} kg$

The motion of each of both reeds can be described by an effective harmonic oscillator equation [4]:

$$\ddot{x} + 2r\dot{x} + \omega_0^2 x = \frac{S\ \ p}{m} \qquad (1)$$

The elongation x corresponds in good approximation to the distance of an arbitrary point at the reed tip to its rest position, the sign of x is determined by the direction of the respective axis in Fig. 1. The pressure difference between both sides of the reed is denoted by p. Following [4], the effective reed area S equals $2/5$ of the actual surface area. Inserting length $14mm$ and width $2mm$ gives the value of S in table 1. A load of $4g$ at the free end of the C-reed causes a deflection of $1mm$. The resulting spring constant has to be multiplied by $16/15$ to give the effective spring constant $D = 42N/m$. Inserting pressure fluctuations around a mean value of $700Pa$ [4] in (1) finally results in reed vibrations around a mean deflection of about $2mm$ from the rest position. For the amplitude of the oscillations, 1.8mm has been applied ad hoc. Fig. 6 was created using these values. It is indeed realistic that the reeds oscillate beyond the openings in the reedplates. When the cover plate is unscrewed, the vibration of the reed is visible and you can feel it with your fingers.

The damping constant $2r$ was determined for the D-reed measuring the relaxation time (cf. my essay "Measurement of relaxation time and damping of a blues harp reed" [6]). It is assumed that both reeds in channel #4 of a C harp share approximately the same values for length, width, thickness, effective spring constant and damping constant. Because of the weak damping of a blues harp reed its natural (circular) frequency ω_0 can be measured by simply plucking the reed and determining the fundamental frequency of the emitted sound. Inserting the resulting values of ω_0 together with the above mentioned effective spring constant $D = 42N/m$ in $\omega_0^2 = D/m$ finally results in the values for the effective masses m in table 1.

According to (1), the amplitude $\hat{x}$ of the oscillation under sinusoidal pressure fluctuations with amplitude $\hat{p}$ is calculated as:

$$\hat{x} = \frac{S\ \hat{p}/m}{\sqrt{(2r\omega)^2 + \left(\omega_0^2 - \omega^2\right)^2}} \qquad (2)$$

In order to estimate the influence of the higher harmonics of the pressure on the oscillating reeds, equal amplitudes of fundamental and first harmonic have been assumed as an example. With $\omega = 3500 s^{-1}$ as the playing frequency, this results in a ratio of $1:25 = 4\%$ for the amplitudes of the corresponding reed oscillations.

For sinusoidal pressure fluctuations with frequency ω a reed with natural frequency ω_0 oscillates phase-shifted by an angle ϕ:

$$\tan\phi = \frac{2r\omega}{\omega_0^2 - \omega^2} \qquad (3)$$

With $\omega = 3500 s^{-1}$, these phase shifts are $\pm 2^0$ for the two reeds in channel #4 of a C harp. This means that the reeds move almost synchronously apart from a phase shift of 4^0.

Literature

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