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The blues harp in frequency domain

Alfred Förtsch

Alzenau. Email: bluesharp-foe@t-online.de

The "Mississippi saxophone" – not a saxophone

Unlike the saxophone, the blues harp (the "Mississippi Saxophone") does not have an instrument body with sharply defined resonances. In addition, each of the ten channels contains two reeds that are only very weakly damped and can vibrate freely through openings in the reed plates ("free reeds"). With a relaxed vocal tract, normal blow and draw notes can be played, with almost only the blow or draw reed vibrating. The pitch is just below the natural frequency of the blow resp. the draw reed. For normal notes, the blues harp is more similar to the accordion than the saxophone.

On the lower channels (and only these will be discussed below), the normal draw note can be "bent" downward. The lowest possible bend sounds almost a semitone above the natural frequency of the blowing reed in the channel. When bending, both reeds vibrate. The deeper the bend, the more the blow reed and the less the draw reed vibrates. Bends are based on resonances inside the vocal tract. However, the resonances in the vocal tract are much less pronounced than the resonances in the tube of a saxophone.

The sound of the blues harp

The notes on a blues harp sound differently "cool." Draw notes sound more "colorful" than blow notes, and bent draw notes sound the most "bluesy." Notes in the middle and lower ranges that are not too deep sound more "expressive" than notes in the high range. Fig. 1 shows an extended minor pentatonic scale in G major, often used in Chicago blues, as it can be played on the lower channels of a C harp. Normal blow notes are marked in yellow, normal draw notes in green, and bends in purple. The good-sounding draw notes predominate (and are therefore mainly played), with the diminished intervals typical of blues (third, fifth, and seventh) being the particularly bluesy-sounding bends.

Figure 1: Blues scale in G on a C harp. Yellow: normal blow notes, green: normal draw notes, purple: bends

The physics of the "bluesy" sound

Are there any physical explanations for the different sounds of normal blow notes, normal draw notes and bends? We will look for the answer in frequency domain, considering only the steady state of tones sounding as uniform as possible. The approach will be to work with a frequency resolution of less than one hertz. Since the frequency resolution is the reciprocal of the duration of the sound, sounds had to be recorded that lasted for several seconds. The criteria for the ultimately subjective selection of the subsequently transformed waves were constant pitch, volume, and intonation (see for example Fig. 2). What we actually hear from such precise frequency analyses would be the subject of further sensory physiological and perceptual psychological investigations [1].

Creating DFTs

For the recordings, the microphone (Sure SM58) was positioned a few centimeters in front of my blues harp. After digitization via an audio interface (Focusrite Scarlett 2i2), the wave files were edited using the digital audio software Audacity. To counteract the occurrence of artifacts when performing the Fourier transform, I cut out waves that looked as "periodic" as possible and converged towards a sample value of zero at the ends of the rectangular window (see Fig. 3). In addition, the two samples at the ends were exactly set zero. The DFTs were calculated by Python using rfft from scipy.fft. The lengths of the cut-out waves were irrelevant, since scipy.fft calculates the DFT exactly for any wavelength [2]. A logarithmic representation of the spectra was not used (see for example Fig. 2) because this would require us to be able to perceive the individual frequencies (which are ultimately a product of discretization).

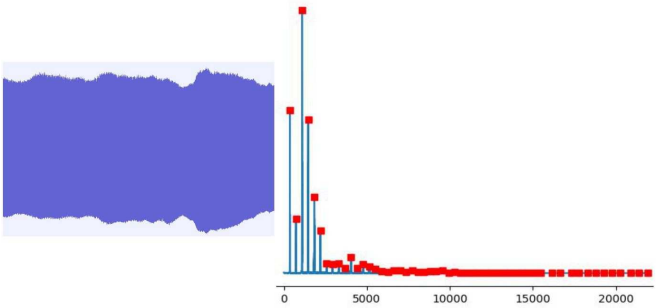

Figure 2: Wave of a whole tone bend on channel #3 of an A harp (left) and maxima of the spectrum (right).

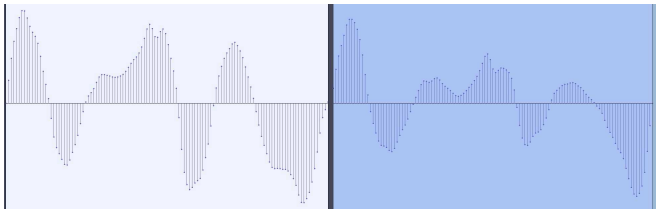

Figure 3: Beginning and end of a "by eye" periodic wave (whole tone bend on channel #3 of an A harp in Fig. 2). The first and last samples were set to zero using Audacity.

Data storage

The draw notes on the lower channels of a blues harp can be bent down continuously to the lowest possible bend, which

is about a semitone above the blow note in the channel. In the following, "bends" refer to notes that are (approximately) in the usual 12-step semitone scale. Three test series were recorded and evaluated: Normal notes and bends on a C harp (a mid-range blues harp), normal notes and bends on channels #3 and #4 of an A harp (probably the most commonly used harp in Chicago blues), and normal notes and bends on channel #4 of blues harps in all twelve keys.

When judging the following analyses, it must be emphasized that several recordings for the same note could lead to different results (examples will be given below). And, of course, one would have to evaluate the sounds of several players, preferably professional ones - not just recordings from me.

Regular overtone spectrum

The maxima of the absolute values of the Fourier coefficients define a very regular overtone spectrum in all my recordings. The frequency f_n of the nth maximum (nth harmonic) is always precisely n times the frequency f_1 of the first maximum (fundamental tone, playing frequency, first harmonic). This statement applies to all normal blow and draw notes and to all bends in the data set. Fig. 4 shows the deviations $f_n - n \cdot f_1$ for the nth harmonic f_n from n times the playing frequency f_1 in cent , exemplified for a normal blow note, a normal draw note, and a whole tone bend on channels #3 of a C harp and of an A harp. Apparently, the "bluesy" sound of bends cannot be derived from an irregular overtone spectrum.

C-Harp							
n-th harmonic	Fundamental (n=1)	n=2	n=3	n=4	n=5	n=6	n=7
Normal blow G4	395,6Hz +/- 0,3Hz	0,0	0,0	0,0	0,0	0,0	0,0
Normal draw B4	497,3Hz +/- 0,2Hz	0,0	0,0	0,0	-0,2	-0,1	-0,1
Bend A4	433,7Hz +/- 0,3Hz	0,0	1,7	1,3	-3,0	0,8	1,1
A-Harp							
Normal blow E4	331,0Hz +/- 0,2Hz	0,0	0,0	0,3	0,2	0,2	0,2
Normal draw G#4	410,4Hz +/- 0,3Hz	-0,6	0,4	0,0	-0,2	-0,6	-0,6
Bend F#4	372,6Hz +/- 0,2Hz	-0,4	-2,6	-1,9	3,9	-0,6	-1,1

Figure 4: Deviations $f_n - n \cdot f_1$ for the nth harmonic (n>1) from n times the playing frequency in *cent* for three notes each on channel #3 of a C harp resp. an A harp: normal blow and draw notes as well as whole tone bend.

Which harmonic dominates?

Fig. 5 shows the spectrum of the magnitude maxima for the DFT of tones on channel #3 of an A-Harp. In my data set, one of the first three harmonics always dominates. Is this dominant harmonic responsible for the different sound of normal blow and draw notes on the one hand and bends on the other?

The colors in Fig. 5 and Fig. 6 indicate which harmonic dominates: yellow denotes the fundamental tone, light blue the first overtone, and magenta the second overtone.

In Fig. 6 (above), amplitude spectra for notes on channel #4 were evaluated for blues harps in all keys (normal blow note, normal draw note, semitone bend). Apart from special models, the G harp sounds the lowest and the F# harp the highest. Fig. 6 (below) shows the dominant harmonics for the specified channels of a C harp and an A harp (normal blow and draw notes, bends by one, two, or three semitones).

For notes lower than C5, the fundamental tone dominates in most normal notes, whereas the second overtone dominates in most bends. A clear correlation cannot be derived from the evaluated waves: Note, for example, in Fig. 6 the different results for channel #4 of the C harp (top versus bottom left) and for channel #3 of an A harp (bottom right) in different recordings.

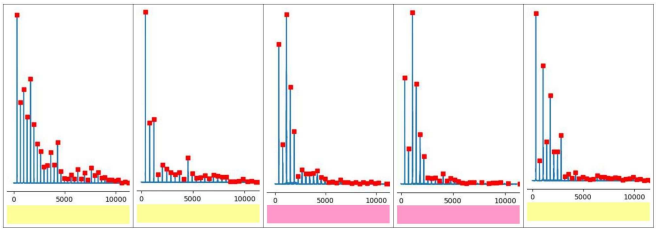

Figure 5: Spectrum with harmonics for notes on channel #3 of an A harp. From left to right: normal blow, normal draw, bends one, two, and three semitones lower than the normal draw note. Yellow and magenta denote the dominance of the fundamental tone and the second overtone, respectively.

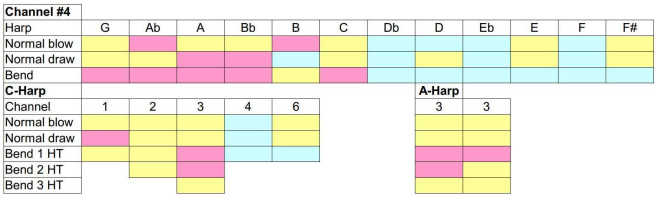

Figure 6: Which of the first three harmonics predominates in normal blow and draw notes or in bends? Yellow = fundamental tone, light blue = first overtone, magenta = second overtone. Top: Channel #4 of the specified harp, bend by a semitone. Bottom: Specified channels for a C harp (left) and an A harp (right), bends for one, two, and three semitones.

For notes higher than C5, the first overtone usually dominates, with no significant difference between normal notes and bends. This corresponds to the impression that semitone bends do not sound significantly "bluesier" than normal notes for higher notes.

The neighborhoods of the maxima

Fig. 7 shows the neighborhoods of the first five harmonics in the frequency domain for a normal blow note, a normal draw note, and a whole tone bend on channel #3 of an A harp. It seems reasonable to assume that the more "impure" the frequency spectrum is, the more "bluesy" we perceive the sound to be.

However, Fig. 7 is only exemplary for channels with lower pitches. Higher bends, on the other hand, show a comparatively "pure" frequency spectrum, see for example Fig. 9 for a semitone bend on channel #4 of a F# harp. This correlates with the fact that one hears fewer differences between the different types of notes at higher pitches, at least for semitone bends.

Interestingly, when bending as low as possible on channel #3 of an A harp as shown in Fig. 5, the fundamental note prevails again (as well as on channel #3 of a C harp), even though this bend sounds rather "bluesy." The dispersion of the spectrum around the maxima, however, resembles the spectra of the other bends on this channel (see Fig. 8 top), while the spectra of the normal tones show almost no dispersion. The bends on channel #2 of a C harp behave in exactly this way (see Fig. 8 bottom), This could be an indication that the dispersion of the spectra rather than the dominance of a harmonic is responsible for the bluesy sound.

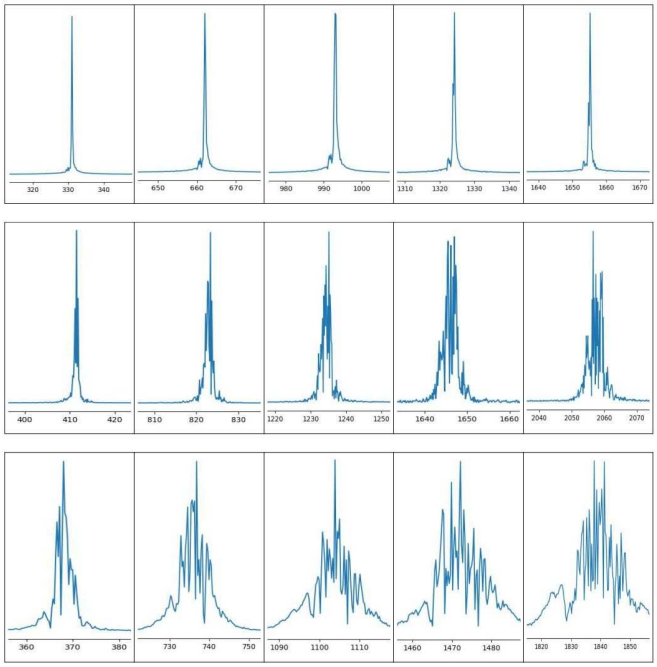

Figure 7: Neighborhoods of the first five harmonics for notes on channel #3 of an A harp. Above: normal blow, middle: normal draw, bottom: whole tone bend.

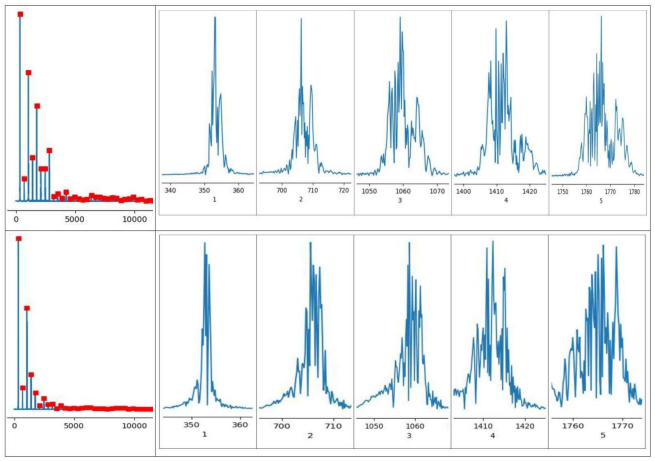

Figure 8: Top: Bend by three semitones on channel #3 of an A harp. Bottom: Bend by two semitones on channel #2 of a C harp. In each case, neighborhoods of the first five harmonics.

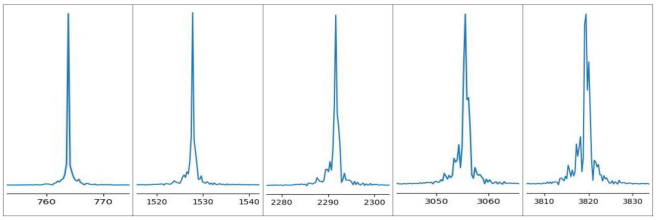

Figure 9: Neighborhoods of the first five harmonics for a bend on channel #4 of an F# harp.

Reed vibrations

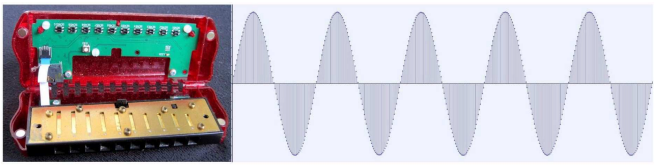

Figure 10: Optical sensors and harp inside an ELX (left). Wave of draw reed motion during a bend on channel #4 of a C harp (right).

The vibrations of the two reeds in a channel can be recorded as a wave using an ELX (a type of "pickup" for the blues harp developed by James Antaki that works with optical sensors, see Fig. 10), although it should be noted that the ELX is a "black box" in terms of measurement technology. The signal from the ELX was recorded with a Zoom H4n and edited with Audacity. To counteract the noise from the optical sensors, Audacity's noise reduction (30dB, frequency smoothing equal to zero) was used. The reeds oscillate in an approximately sinusoidal manner, so that waves could be cut out that begin with a sinusoidal curve (based on visual estimation) with a zero sample at the beginning (see Fig. 10). Relative to these sine waves, phase shifts for the individual frequencies can be calculated from the complex values of the Fourier transforms, especially for the maximum frequency. Using iffft from scipy.fft, the Fourier transforms for individual frequencies and for frequency intervals can be inverted back.

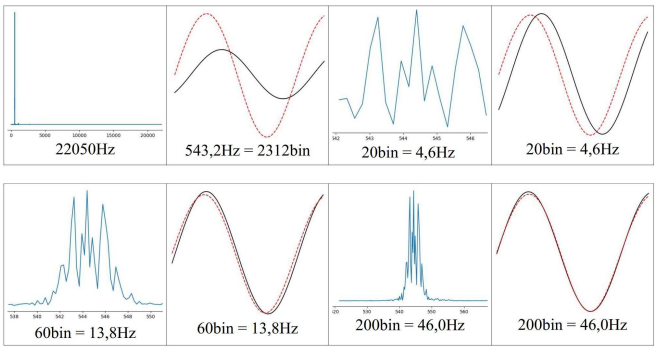

Figure 11: Movement of the draw reed during a bend on channel #4 of a C harp. Blue: Spectra at intervals of the specified lengths. Red: Wave of the reed movement. Black: Inverse Fourier transform on the interval of the specified length with the maximum frequency in the center.

Fig. 11 relates to the movement of the draw reed during a bend on channel #4 of a C harp (the frequency resolution is 0.12Hz). The Fourier transforms over an interval of the specified length are shown in blue. The first 100 samples of the wave supplied by the ELX are shown three times in red. The curves in black are the inversions of the Fourier transform for the maximum frequency and for restrictions of the DFT to intervals of the specified lengths (values not equal to the maximum frequency or outside the intervals set to zero).

The "eyeball" sinusoids of the draw reed and the inversion for the maximum frequency are phase-shifted by 48.3°. Averaging over an interval of 60bin=14Hz causes the phase shift to approximately disappear.

Since the ELX is a "black box," the widening of the maximum peak in Fig. 11 may be an artifact. Explanations of bends in the frequency range as in [3] (which assume sharply defined frequencies and phases) should nevertheless be viewed critically. Both the assumption of a sharp resonance frequency of the vocal tract and the assumption of strictly sinusoidal movements of the vibrating reeds should be confirmed experimentally. An alternative would be qualitative explanations and numerical simulations in time domain.

Results

If a frequency resolution of less than one hertz is used, the overtone spectrum of the notes played on a blues harp is extremely regular for all kinds of notes, including bends.

From a physical point of view, the "bluesy" sound of bends in the middle range of blues harps can be explained by the dispersion of the magnitude spectrum around the maximum magnitudes.

The movements of the reeds are approximately sinusoidal. On closer inspection, the dispersion around the maximum also plays a role here. In order to reconstruct the wave of the reed movement using inverse Fourier transformation, a relatively wide interval around the maximum frequency must be taken into account.

References

[1] Moore, Brian CJ. An introduction to the psychology of hearing. Brill, 2012

[2] scipy.fft manual
URL:`https://docs.scipy.org/doc/scipy/reference/gererated/scipy.fft.fft.html`

[3] Johnston, R. B. (1987). Pitch control in harmonica playing. Acoustics Australia, 15(3), 69-75