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Resonator Guitar Physics Clue from a Paper Cone

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Resonator guitars are distinguished by the thin aluminum cone or cones that convert string vibration to air vibration. Substituting paper for that aluminum demonstrates that much of what distinguishes them from other guitars comes from basic features of design rather than particular features of the cone(s).

Different cones may be more or less to individual players' liking, and paper is an unlikely choice. However, recorded comparisons to flat-top guitars presented here, including sound files, admittance measurements, spectra, and spectrograms, suggest that the characteristic, identifiable commonality of resonator guitar sound is produced by well-defined frequency components that are not related to the pitch of the strings. A natural hypothesis is that these "other" components come from resonances of parts of the body that are excited by the sudden disturbance created by a pluck. As yet to be determined are which parts contribute most strongly to those sounds and exactly how they are excited.

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I. INTRODUCTION

Resonator guitars were invented about a hundred years ago, prompted by a request for a guitar whose volume could compete in the context of jazz bands. Electric amplification rendered them obsolete nearly at birth. Nevertheless, to this day, they remain a favorite with some folks for their sound, which is distinct from that of any other string instrument.

When addressing the resonator guitar in the context of the acoustics of musical instruments, there are two central questions. First: what characteristics of the sound are common to the many variants of resonator guitars that make them identifiably distinct from other acoustic guitars? To connect to physics, those characteristics would have to be identifiable in recordings and quantifiable to some extent.

Second: what aspect of resonator guitar construction is responsible for the characteristic sound? In particular, how does it work in terms of physics? Addressing this question requires knowing what aspect of the sound deserves particular attention. The physics may prove to be quite challenging because the relevant vibrating system is likely not one for which there is an analogous ideal system. Idealizations of strings, bars, thin plates, and drum heads have contributed to understanding not only the common basics of all string instruments but also some of their individual, distinct features. The relevant distinguishing physics of resonator cones and resonator guitar bodies might not have simple, quantitative paper-and-pencil descriptions. The only physics perspective offered at the end of this study is qualitative, inspired by the details of the design and features of the sound recordings.

II. HEAR FOR YOURSELF

This effort only makes sense if there is something special in the sound and not just the appearance or the history of the resonator instruments. For anyone not personally familiar with resonator guitars, a short sample of the same music is played first on a steel string, flat-top, acoustic guitar and then on a fairly standard (biscuit bridge, single cone, brass body[1]) resonator guitar.

Then, recordings of the same short selection are presented for two different flat-top guitars, two resonator guitars (one brass body and one steel, with different aluminum cones), and two radical substitutes for the aluminum cone (mounted in the steel body). One substitute is made of 100 lb cardstock, fashioned rather like the original aluminum cone and the other is just silly. See FIG.s 1 & 2. However, the recordings are labeled A through F. Even people without resonator guitar experience can tell which are the flat-tops and which are the resonators.

FIG. 1: 100 lb cardstock cone & standard aluminum

Hear flat-top first and then brass/aluminum resonator:
http://www.its.caltech.edu/∼politzer/paper-cone/KC-sp+5dB-then-royall.mp3
When played and recorded similarly, the resonator is considerably louder. To help focus on timbre, the flat-top has been boosted by 5 dB to produce similar loudness in the playback.

The following sound files are the same short selection, loudness roughly equalized, for the six instruments described above. Your task is to identify which is which. (Good ears and good speakers will help.)
http://www.its.caltech.edu/∼politzer/paper-cone/guitar-ID-challenge/A.mp3
http://www.its.caltech.edu/∼politzer/paper-cone/guitar-ID-challenge/B.mp3
http://www.its.caltech.edu/∼politzer/paper-cone/guitar-ID-challenge/C.mp3
http://www.its.caltech.edu/∼politzer/paper-cone/guitar-ID-challenge/D.mp3
http://www.its.caltech.edu/∼politzer/paper-cone/guitar-ID-challenge/E.mp3

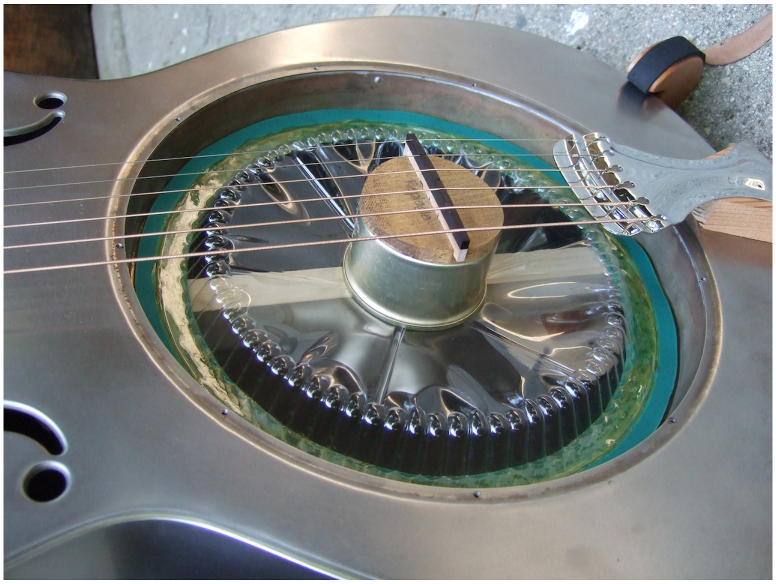


FIG. 2: a PETE #1 take-out container lid as a cone substitute

http://www.its.caltech.edu/∼politzer/paper-cone/guitar-ID-challenge/F.mp3

All six files are in the folder http://www.its.caltech.edu/∼politzer/paper-cone/guitar-ID-challenge/.

Appendix A on p. 18 provides the answers.

Note added: The relation of resonator cones to paper speaker cones is well known to cone makers as well as to many builders and players. A Web search on `resonator guitar physics` *turned up a link to a decade-old resonator discussion thread which included a link to another site. That link was to a video by a fellow whose home-made guitar was, indeed, based on a paper woofer cone, mounted in a rectangular wood and fiberboard box for a body. The sound is convincing, but no further information has turned up as yet. Here is the original: https://www.dailymotion.com/embed/video/x21h18r, and here is where I first found it, near the bottom of page 1: https://michaelmesser.proboards.com/thread/7581/resonator-cone-physics.*

III. RECORDED SINGLE PLUCKS & ADMITTANCE MEASUREMENTS

Spectrograms of microphone recordings of single plucks will reveal some features common to the resonator guitars and absent from the flat-tops. But attempts to connect details of microphone sound recordings with physical properties of instruments have potential perils. In contrast, direct string-to-bridge admittance measurements reflect properties of the instrument itself, relatively free of details of placement of instrument and microphone and the room. Below, there is a brief general discussion of the pros and cons. (See ref. [2] for some details.) Then, some carefully controlled, microphone recordings of single string pluck sounds are analyzed. That is followed by crude estimates of the relative magnitudes of the point admittance at the bridge.

A. pluck sound recording *versus* admittance

Loop very thin copper wire around a guitar string and pull until it breaks. That produces a very reproducible pluck, and its sound can be recorded with a microphone. If the wire is looped right at the bridge with all strings damped, it is a simple alternative to a precision impulse hammer. The consequent motion of the bridge at that point is characterized by the admittance. In particular, admittance is the velocity of the bridge at that point divided by the applied force, usually expressed as a function of frequency. The wire-break produces a sharp step in the force on the bridge. The step is equivalent to a sum of sinusoidal forces, and the function of frequency is computed *via* Fourier transform. Admittance is a complex function, with real and imaginary parts separately representing energy back-and-forth and energy absorption.

Many features of a sound recording depend on the geometry, i.e., the location and orientation of the instrument and microphone within the surrounding space. Furthermore, those effects are frequency-dependent. When comparing small differences between instruments, those differences might be enhanced or reduced, depending on the geometry being used. A slight change of geometry between recordings might confuse the issue.

A measurement of admittance is far less sensitive to the surrounding space. The measurement method of choice in the 21$^{\text{st}}$ Century is a laser Doppler vibrometer, which records the velocity as a function of time at the point where the laser beam is reflected back to the device. A low-tech method that can give some useful information uses a microphone placed as close as possible so that it is most sensitive to the "near-field" vibration of the air right around the bridge.

B. controlled pluck sounds

Wire-break plucks were recorded on all instruments with a directional microphone at $3'$, pointed at the bass side of the upper bout, with the same geometry and recording volume, using 42 AGW magnet wire ($0.0024''$ diameter). The plucks were at the 12^{th} fret on the 1^{st} string, perpendicular to the string and parallel to the top of the body, with no damping of strings. For each resonator guitar pluck, the protective cover plate or grill was installed — because that is how they are normally played. To allow access to the bridge for the admittance measurements described in section §IIIC, the *bridge* cover (aka palm rest) was **not** installed for any of the recordings. See FIG. 3. (Even when installed in place, those bridge covers leave a substantial portion of the biscuit uncovered.)

FIG. 3: cover plate installed, bridge and biscuit uncovered, and tailpiece modified to get a 4° break angle with the aluminum & cardstock cones

FIG. 4 shows the waveforms of five successive plucks on one of the instruments — in particular, the steel body with the PETE lid "cone." There certainly are differences between them, but those differences are much smaller than the differences between instruments. FIG. 5 shows one representative waveform for each of the six instruments.

The plucks on a given instrument were so similar and the plucks on different instruments so distinct that only a single representative pluck for each instrument is considered in the discussions that follow.

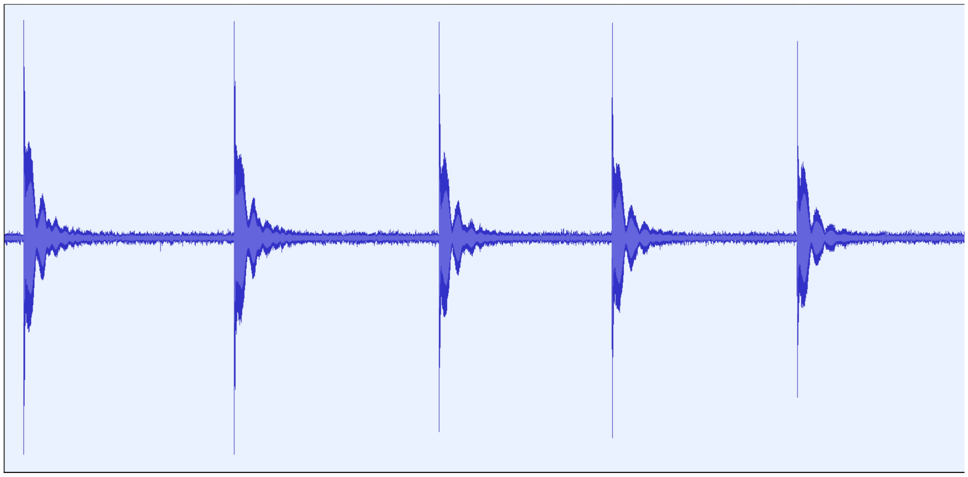


FIG. 4: 1st string wire breaks at the 12th fret on the PETE lid resonator

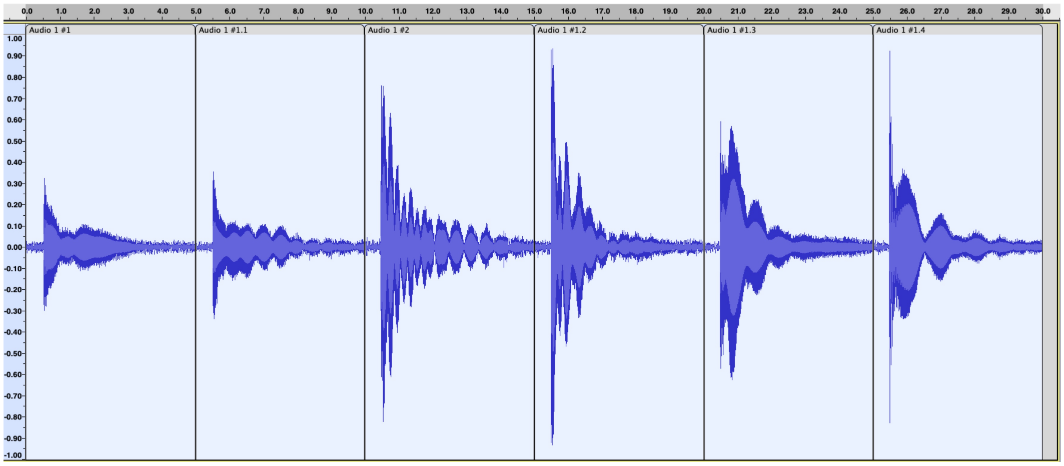


FIG. 5: 1st string at the 12th fret; left to right: 2 flat-tops, 4 resonators – see text

In FIG. 5, the first two waveforms are from the two flat-top guitars. The other four are resonators. All six are shown with the same recording volume and amplitude scale. Indeed, resonator guitars are louder. From left to right, the resonator guitars are: brass body/aluminum cone, steel body/aluminum cone, steel body/paper cone, and steel body/PETE lid.

These are the sounds of the recordings in that same order:

http://www.its.caltech.edu/∼politzer/paper-cone/sp-ym-ry-rp-gr-ld-1pluck-original-volume.mp3.

The point at which the wire loop is applied impacts the spectrum of the string's response. In particular, string modes are suppressed to the extent that they have a node near the wire-break location. Locating at the 12th fret imparts a particularly simple pattern on the general $1/n^2$ envelope of the string frequency spectrum. The even-n modes are absent. Those will appear in the sound, due to imperfections and various interactions between parts of the instrument.

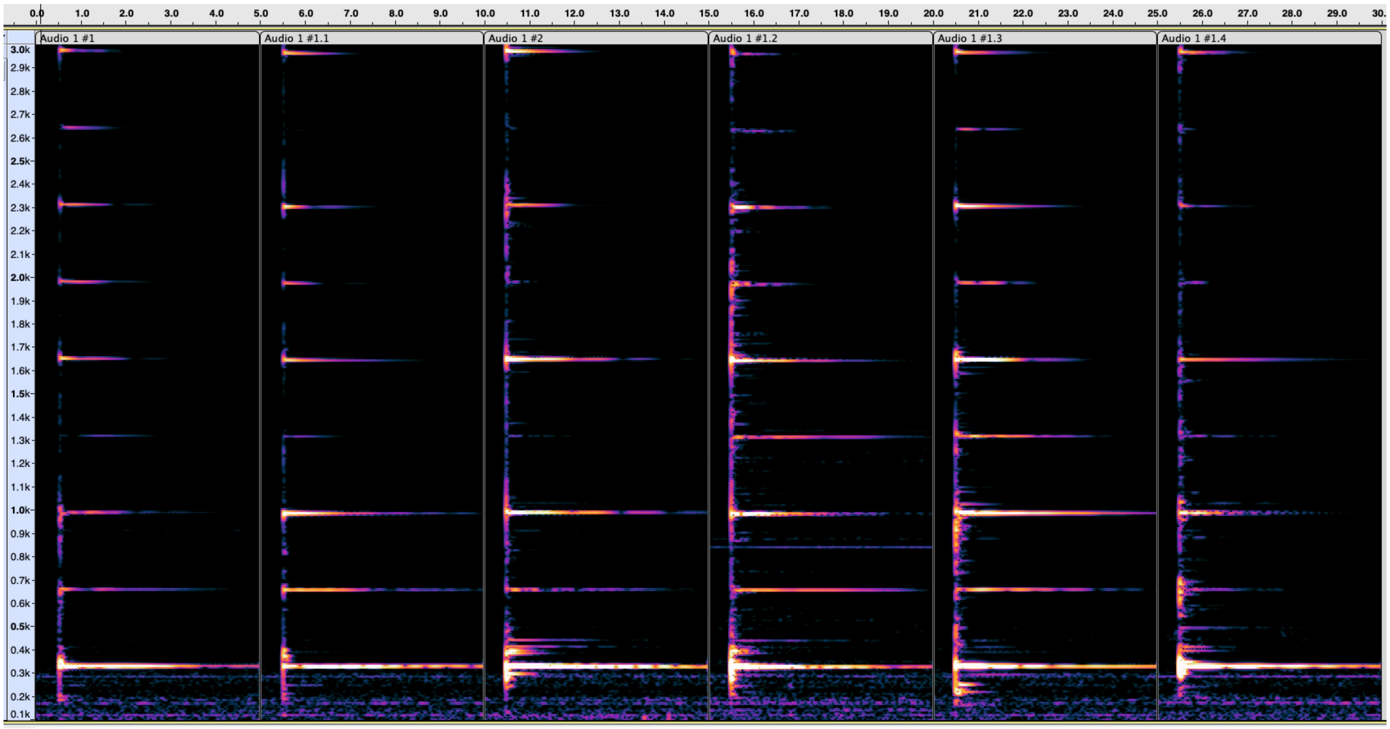


FIG. 6: 1st string wire breaks at the 12th fret on each instrument — in the same order as the sound sample; see text for IDs and Appendix C for a larger version of this image

FIG. 6 shows a spectrogram representation of each of the six plucks. Each is 5.0 seconds long — the same as in the mp3 above. The displayed frequency range is 0 to 3000 Hz. A feature that persists over the whole audible frequency range is most evident in this range. The two flat-top guitars show little persistent sound besides the equally-spaced frequencies expected from the string harmonics. In contrast, *all* of the resonator guitars show narrow peaks that decay faster than the string harmonics but persist well beyond the initial broadband noise.

These "extra" frequency peaks are likely a key to the origin of the characteristic resonator guitar sound. Section §IV gives a general account of how such peaks can arise. This applies to any stringed instrument. And section §V offers some discussion of why they are so relatively strong on resonator guitars.

C. crude admittance measurements

How the strings drive the bridge is obviously an important aspect of any stringed instrument. For the banjo — and even guitar and violin — it captures a large part of the story. In those cases, a model of string physics can be coupled with a measurement or calculation of the bridge admittance. If the resulting functions are translated into voltages to drive a speaker or create an audio file, the resulting sound has many of the features of an actual instrument. It's not quite right, but the bridge drives the soundboard, and that's most of the story.

Resonator guitars are different. The bridge drives the resonator cone, but the cone is covered with a grill. That alters the sound. (The difference was illustrated in the second paper of ref. [1] and is reproduced in section §C1 below.) As pictured in Fig. 7, an instrument was constructed where the resonator cone was, indeed, the soundboard.[1] The rest of the body was relatively rigid and not a good radiator of sound. With the same string material, gauge, scale length, and tension, the sound is definitely not that of a resonator guitar. It is weaker and different in detail. In a resonator guitar, the two sides of the cone are typically segregated by a solid wall. It is part of what is known as the "sound well," which also includes the shelf on which the cone rests.[1] Some of the air disturbance created by the top or front comes out the holes in the grill, but some is reflected back onto the cone. The air disturbance on the other side of the cone propagates into the body. Hence, the relation of the total sound production to the vibration of the cone is rather more complex than it is with a direct soundboard.

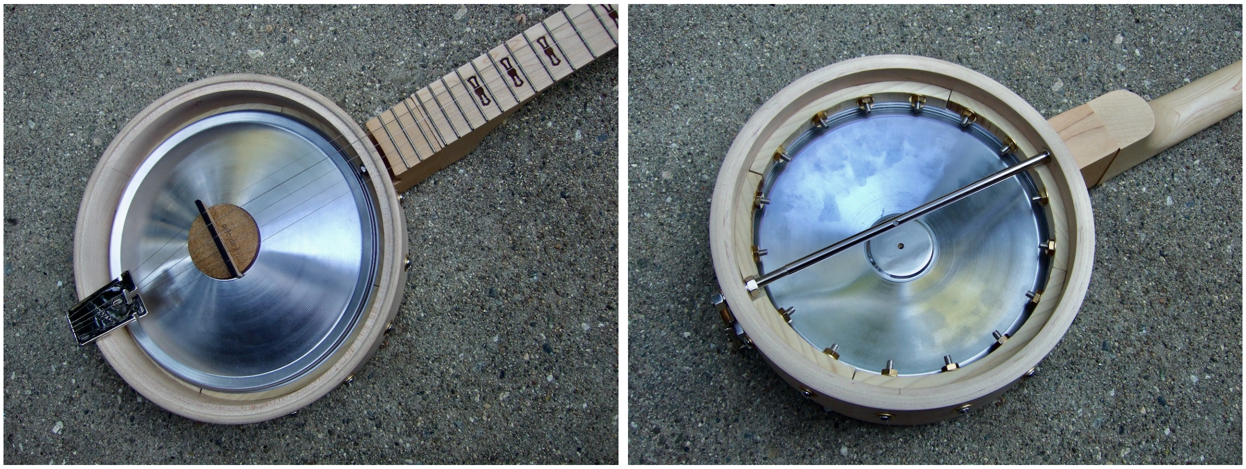


FIG. 7: the "banjo" mounted resonator cone used in these previous investigations

FIG. 8: surface variation can impact interpretation of near-field recording

On a banjo or flat-top guitar, near-field microphone recordings can capture a reasonable approximation to bridge motion because the bridge sits directly on a flat surface. FIG. 8 shows the situation on the brass body resonator used in this study. The microphone picks up motion of the bridge and the $2\frac{1}{2}''$ diameter biscuit on which it sits. The cone slopes down from the edge of the biscuit (at about 18°). And the biscuit top sits slightly below the grill cover, which has a hole somewhat bigger than the biscuit. The air flow pattern must certainly be more complicated right there than it is at the base of the bridge of a banjo. Therefore, the microphone signal is more sensitive to positioning than with the banjo.

In practice, the visible variations that occurred when attempting to reposition the microphone in the same way each time were much smaller than the variation from one instrument to another. To address the positioning sensitivity, the spectra presented below represent the average for each instrument of eight slightly different positionings, all nominally attempting the same near-as-possible geometry. The spectrograms and actual sound files use a single, typical wire-break for each instrument.

1. *banjo, solo cone, resonator without grill, resonator with grill, & flat-top comparison, summarized from ref. [1]*

Here are some relevant results from the second paper of ref. [1].

This is the sound at the bridge of a wire-break, also at the bridge, with all strings damped on five instruments. The order is banjo, cone mounted in a banjo frame as shown in Fig.7, a resonator guitar without its grill cover, the same resonator guitar with grill install, and a flat-top guitar: http://www.its.caltech.edu/∼politzer/paper-cone/Goodtimebanjo-banjores-resun-rescov-guit-same-force-same-percent.mp3.

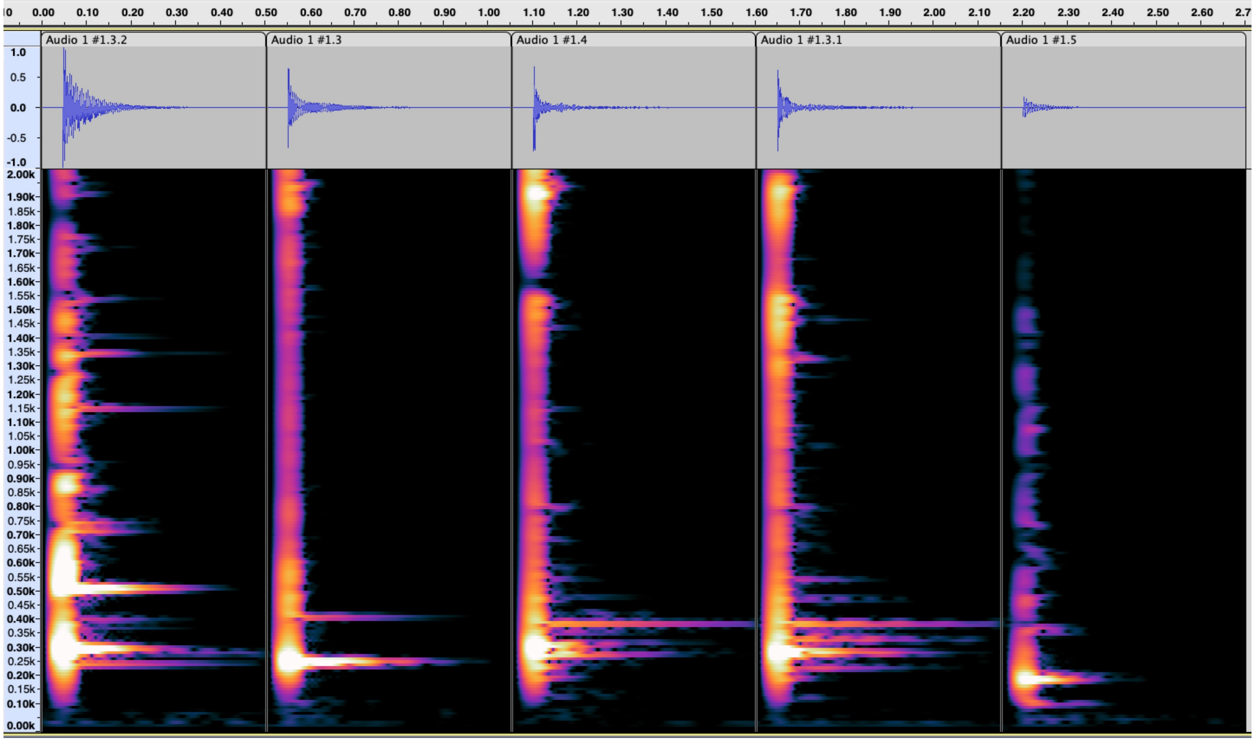


FIG. 9: wave forms and spectrograms of the ref. [1] five damped-string plucks at the bridge

Fig. 9 displays spectrograms of those five recordings. The first on the left is an open-back banjo. It's loud and noisy, and that's its charm. Next is the near-field sound coming off the top of the instrument shown in Fig. 7 — essentially the front (or top) of an aluminum cone by itself. The cone is the same one as used in the steel-body guitar of the current series of comparisons. In the frequency range of the plot, i.e., up to 2 kHz, there is only one prominent resonance in addition to the lowest rigid cone or piston motion (described in section §V).

The next two columns are the resonator guitar, without and then with its grill cover. They are not quite as raucous as the banjo, but there certainly are many identifiable resonances. Note that much of the response to the wire-break is stronger with the cover than without.

The last column is a flat-top guitar. It is not as loud as the others, and the only instrument with fewer visible peaks is the cone by itself, in column 2.

Played music samples of all five instruments are also included in ref. [1].

2. the six guitars of the current investigation

This is the sound of the damped-string wire break at the bridge, recorded with the microphone as close as possible to the bridge on the six guitar variants of the current investigation: http://www.its.caltech.edu/∼politzer/paper-cone/damped-bridge-plucks-1.0sec-6instruments-in-order.mp3. (Again, good speakers and good ears will help.)

These sounds have a qualitative interpretation. The strong component frequencies are, in fact, the same ones as produced by the sudden disturbance created by a normal pluck — as explained in section §IV. The actual relative amplitudes of the various components will be different in the two cases, i.e., a normal open string pluck *versus* a damped string wire-break at the bridge. But these damped-string sounds are a hint of what each instrument's body will add to the string pitch harmonics. The undamped string pitch sounds are, of course, much stronger and persist longer.

FIG. 10 displays spectrograms of the six damped-string wire breaks.

FIG. 11 displays Audacity®-computed spectra of the first second of the recorded sounds. The wire breaks produce nearly identical forces on the bridge (because the instruments have the same strings and tunings). Spectra are proportional to the magnitude of the air pressure and do not contain information about the phase. So, this signal tracks the magnitude of admittance but not real and imaginary parts separately.

Any analysis of frequency components is subject to a mathematical constraint on the frequency and time resolutions. As one resolution gets better, the other must get worse. The spectrum calculation displayed in FIG. 11 has lost all time dependence of the sound within the 1 sec recording interval. Very short-lived components can appear as very strong peaks. In a spectrogram, a compromise is chosen by the investigator between time and frequency. To see fine frequency features, the time resolution is blurred somewhat. The

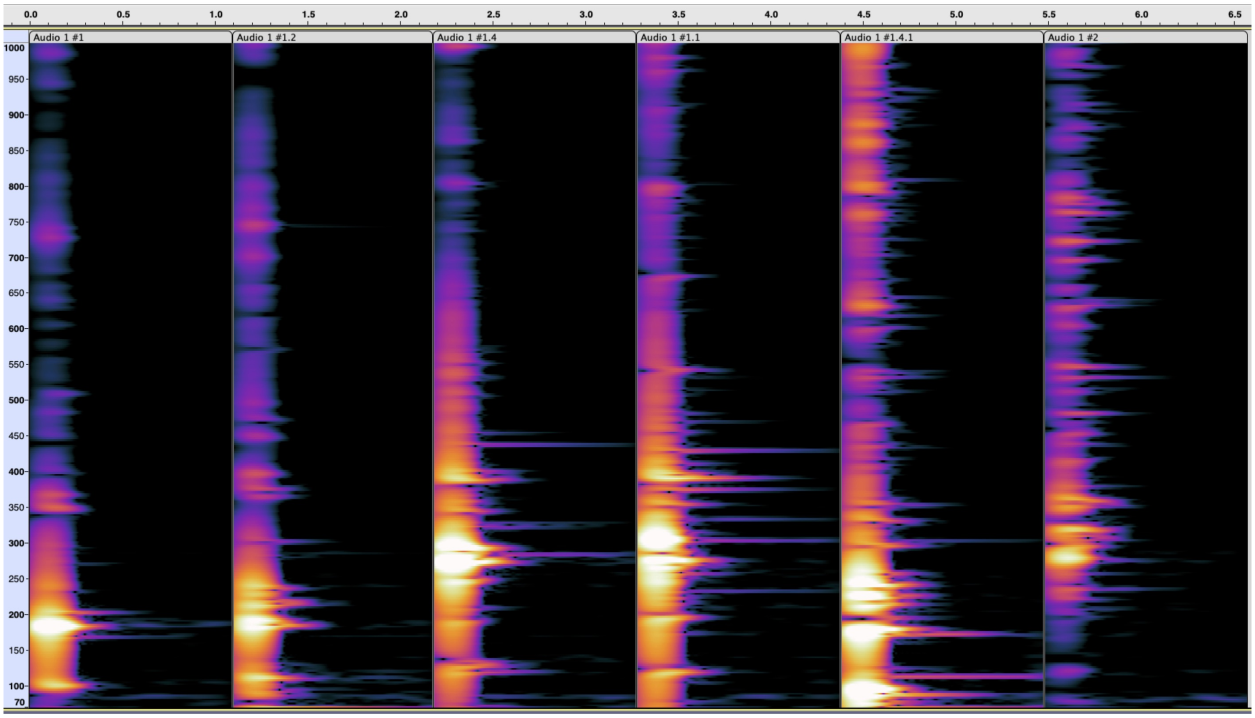


FIG. 10: 70 to 1kHz, 1 sec spectrograms of damped-string wire breaks on the six guitars in the same order

very strong short-time features that occur at the outset of the sound all appear in the initial blur. Evidently, there are a great many resonances with very sort lifetimes. The fine features of interest in the present discussion persist significantly longer, making them quite visible in the spectrogram choices used for FIG. 10. However, many of them are not particularly noticeable in the FIG. 11 spectrum.

Our brains do a marvelous job of analyzing aspects of sounds in parallel. That can result, in the end, with a simultaneous perception of very fine time **and** frequency resolution. Hence, doing the mathematical analysis in more than one way can reveal features of interest to listeners.

A rather remarkable insight due to Skudrzyk[4] is that, in these sorts of situations, the frequency dependence of the admittance averaged over individual resonances reflects the propagation of outgoing waves of the vibrating surface. When banjos were compared to acoustic guitars, a difference in the underlying trends was immediately apparent.[3] That is connected to the banjo soundboard being a membrane with tension as its primary restoring force. In contrast, the guitar has a “thin plate,” whose restoring force is stiffness.

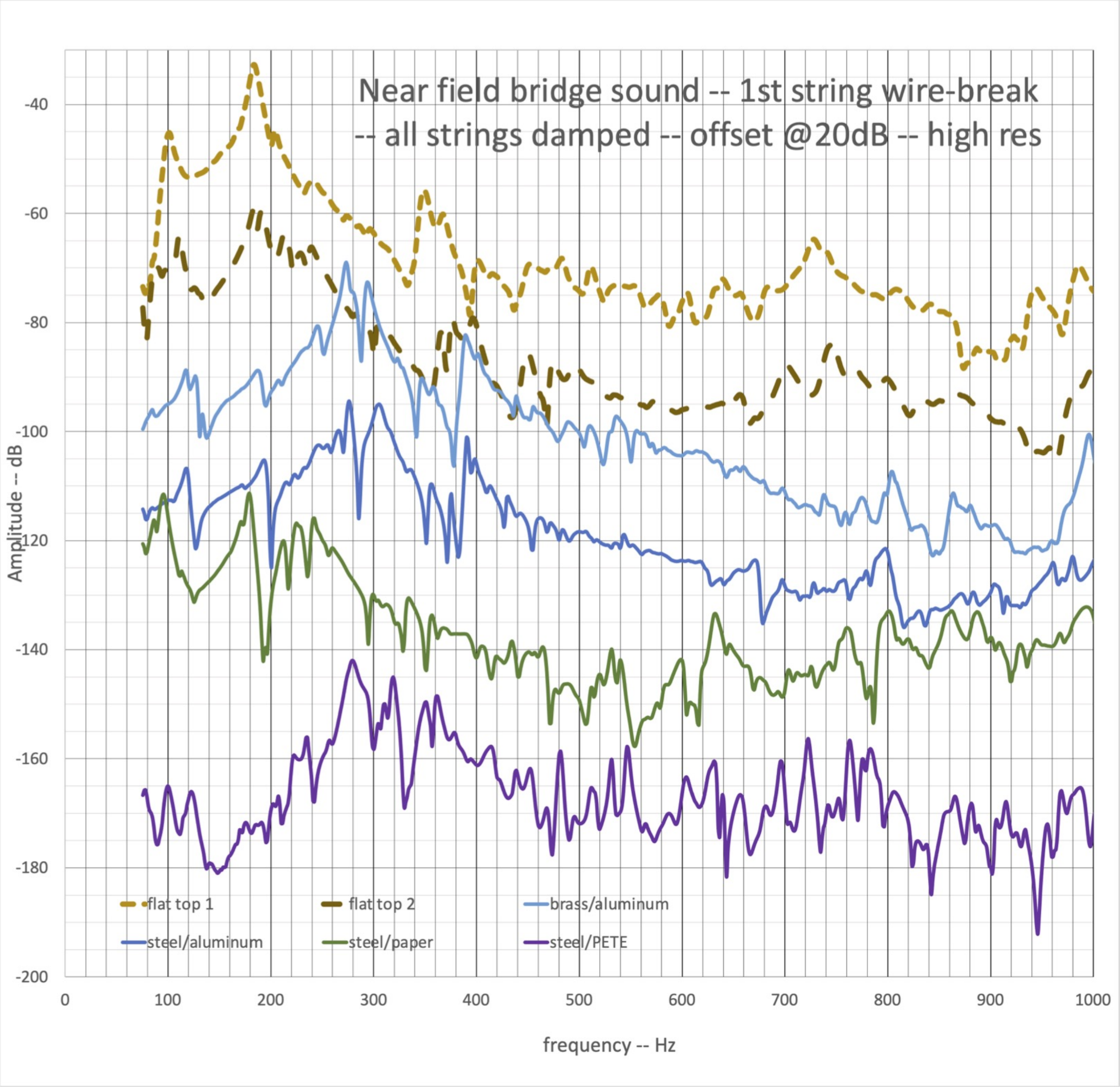


FIG. 11: 70 to 1kHz, 1 sec spectrograms of damped-string wire breaks on the six guitars in the same order, successively offset by 20 dB

FIG. 12 displays the spectrum evaluations for the same six, 1 sec recordings using a frequency resolution that is a factor 64 lower than used for FIG. 11. The lower resolution makes the average trends more apparent. The message of FIG. 12 is that in all these instruments the strings drive a thin plate. The salient differences between the instruments are that the flat-top guitars are not as loud as the resonators.

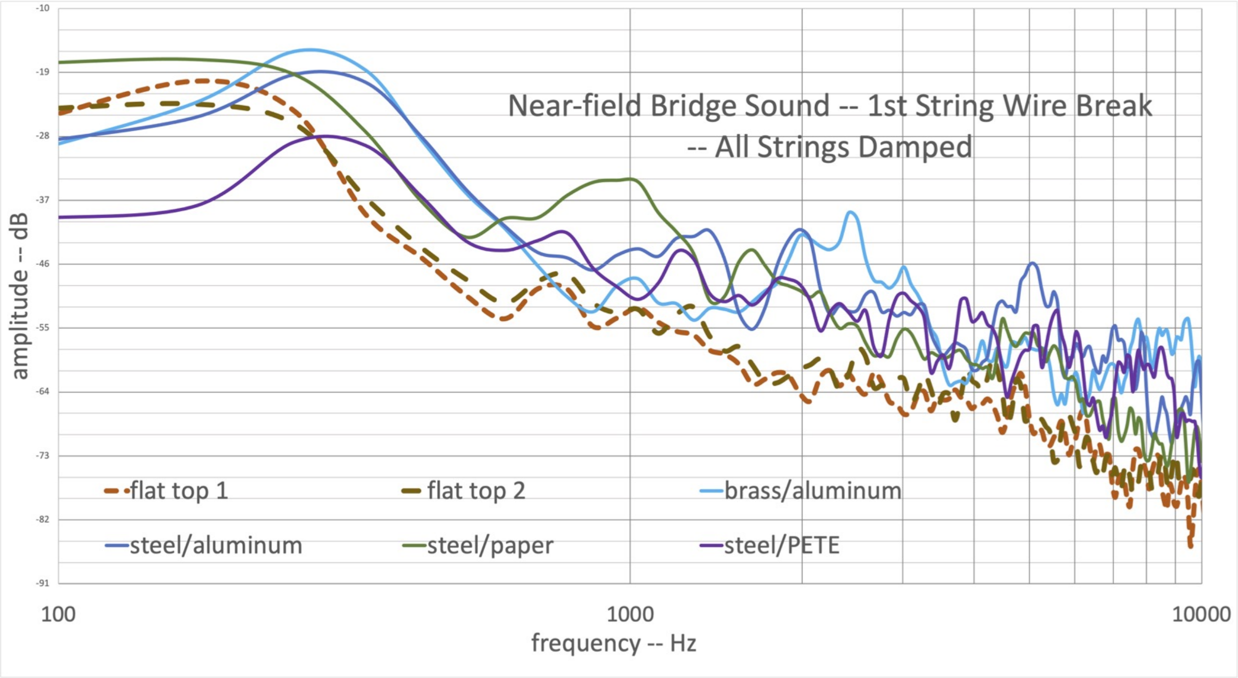


FIG. 12: near-field sound admittance recording spectra — at low frequency resolution

IV. SPECTROGRAMS SUGGEST THAT SHORT-TIME PEAKS DISTINGUISH RESONATORS FROM FLAT-TOPS

In a proper string instrument, the strings vibrate through many cycles before their motion damps away. This produces strong sounds at string frequencies and harmonics. However, the sudden onset of string motion as initiated by a pluck actually excites all the resonances of the instrument that have any connection to the strings. For the system to work as a musical instrument, these other resonances must be short-lived compared to those of the strings and/or produce much less sound.

A simple physics analog is a sinusoidally driven, damped, harmonic oscillator. If the driving is turned on abruptly at $t = 0$ (and zero before), then the resulting motion is the sum of two parts. There is the “persistent” solution at the driving frequency. Its amplitude and phase are determined by the applied force — and are the same as would be if the force existed $-\infty < t < \infty$. The second part is the free decay of the oscillator at its own natural frequency. The two free parameters of such solutions must match the initial $t = 0$ conditions that exist when the persistent solution is included. A spectrum or FFT of the total motion will therefore have two strong components.

This example of the driven, damped harmonic oscillator is worked out in detail in ref. [5] That solution has an important qualitative lesson about the amplitudes of the free-decay component that has the oscillator's own frequency. Of course, that amplitude is largest when the driving frequency is near the free-decay frequency. But we also learn that free-decay amplitudes are small when excited by the onset of lower driving frequencies. Those amplitudes have a factor of the square of the driving frequency divided by the oscillator natural frequency. However, a given driving frequency is roughly equally effective at driving all natural frequencies below it. In a system with many drivers (e.g., the string harmonics) and many damped oscillators (e.g., the guitar body), the body excitations are expected to pile up at the lower frequencies. (That is, indeed, a feature of the resonator guitar spectrograms.)

Viewing the string harmonics as a set of sinusoidal driving forces applied to the bridge, their sudden onset will excite resonances of the guitar body. Some of those will be efficient radiators of sound, but they are certainly shorter-lived than those of the strings.

Presumably, these are the "extra" peaks in the spectrograms in FIG. 10 (and Appendix C). Confirming this identification would require matching vibration measurements of body parts to the observed extra frequencies. Alternatively, a finite-element calculation of the body vibration could identify where these frequencies originate.

V. CONJECTURE: PISTON MOTION OF THE CONE IS RESPONSIBLE FOR STRONG FREE DECAYS

These extra, short-lived frequency components are produced by all acoustic string instruments. The issue is a matter of degree. Slight differences distinguish one individual instrument from another in the same general category. But categories of instruments can be significantly different as a consequence of design. Fine violins and guitars are somewhat quieter than crude ones in this aspect. Banjos are champions. "Extra" frequency components are a big part of banjo sound because the string harmonic components of the sound decay quickly due to the lower impedance mismatch of strings to head and the radiation efficiency of the head. And the most effective "body" resonances are those of the head itself. Resonator guitars apparently fall somewhere in between.

In the examples presented here, the extra peaks are apparent for all four variations of resonator guitars and far weaker for the two flat-top guitars. (Of course, the spectrogram display parameters were chosen to highlight those differences.) A natural conclusion is that those peaks represent the characteristic resonator guitar sound as it is distinct from other acoustic guitars.

And the design of the resonator guitars rather than the material is apparently the source of the distinction.

The decade-plus-old video linked on the bottom of page 4 is another example of resonator sound being produced by a paper cone. In that case, the body is simply a rectangular box constructed of wood and fiberboard. Because the cone is an actual, complete woofer with its original rubber surround, the connection to the bridge is necessarily quite different from what was used here.

The conical shape of the thin materials provides a substantial increase in stiffness against further bending.[6] Aluminum resonator cones are also much like speaker cones in another way. Like speaker cones (woofers especially), resonator cones have a very flexible ring around their periphery. On speakers, this is sometimes called a "surround" or "bellows" and might be a half-round cross section ring of thin rubber. On resonator cones, the same role is played by a narrow outer region with several successive sharp bends. Both speaker and resonator cones are held rigidly around their edges. However, when the center is forced up and down, the surround flexes, and the conical part moves up and down but retains its shape. This piston-like motion gives a response that is smooth as a function of forcing frequency. The smooth response peaks at a resonant frequency determined by the cone inertia and the return force of the surround and, in the case of resonator guitars, the strings.[7] The cones distort at higher frequencies. With speakers, this is known as "break up." Cross-over circuits are designed to avoid those frequencies. These are the peaks in FIG. 7 of the second paper of ref. [1] that come after the broad ones centered around 300 Hz.

Resonator cones are light and move easily compared to the wood soundboards of flat-top guitars. So, they are better transducers of string vibrations to air vibrations. However, the direct sound off the front or top face is partially blocked by the grill. Also, by itself, that sound is not a likely candidate for the signature resonator guitar timbre. That is the lesson of the instrument pictured in FIG. 7 and its spectrogram in FIG. 9, column 2.

A. the remaining BIG QUESTION

While the relatively very light and easily movable cone is responsible for the inherent loudness, it is likely that the resonator guitar body designs are intentionally noisy. Unanswered at this point is how the on-set of the bridge motion excites those noisy body modes. There are two categories of possible mechanisms, and both may be relevant. 1) The piston motion of the cone produces a relatively sudden increase in air pressure inside the body. That can set various parts shaking. And 2) since the surround or bellows of the resonator cone is folded aluminum rather than flimsy, thin rubber, part of the initial impulse accompanying bridge motion is transmitted to the sound-well shelf. That is mechanically connected to the body, either the top or the bottom, depending on design. That initiates vibrations throughout the body. Any other method of supporting the bridge, e.g., the paper cone or the PETE lid can likewise produce a jump in inside air pressure and a vibration of the solid body parts. Their effectiveness at doing one or both of these will presumably determine whether they sound like resonator guitars.

B. “metallic” sound

In 1973, Chowning applied frequency modulation to a pure tone. When the modulation frequency was itself in the audio range, the sound developed a timbre that he described as metallic.[8] The math is familiar from FM radio. The frequency modulation produces frequency sidebands to the carrier or initial sinusoidal signal.

It is obvious what this has to do with metallic sound. Virtually all metal objects (besides taut, thin strings) have resonances that are nowhere near harmonic ratios. The resonance Q-factors (lifetime divided by decay time) are often large compared to non-metallic materials. Some of those resonances are efficient radiators of sound. Hence, the total sound of a struck piece of metal has a mix of “unrelated” frequencies. That is a key part of metallic sound.

Appendix A: ID answer key & longer sample recordings

The six 6 sec samples in section §II are labeled A through F. The identifications are as follows: A = flat-top #2; B = steel body/aluminum cone resonator; C = steel body/paper cone resonator; D = steel body/ PETE lid “cone”; E = flat-top #1; and F = brass resonator/aluminum cone. Note that flat-top #1 is the one used in the first comparison sample in §II.

Recordings of a one-minute music selection that includes notes up the neck are in the online folder http://www.its.caltech.edu/∼politzer/paper-cone/KC-volume-adjusted for each of the six guitar versions. These are also loudness-adjusted as indicated in the file names.

Appendix B: instrument descriptions

1. cones

Many, many materials and designs were attempted to get a non-metalic cone that would work in a resonator guitar. A significant factor is the ability to withstand the static down-pressure of the strings. No attempt at further improvement was attempted after finding something that worked and was relatively easy to fabricate. The material is 100 lb cardstock. White glue holds the radial cone seam and flat cap, and contact cement was used to attach a flat ring, 3/8″ wide, under the outer edge of the cone to increase rigidity there. As shown in FIG. 1, there are two extra folds near the edge, creating slopes before the loading by the strings determined by the deficit angle of the cone. For small, static displacements, the flex is entirely at the folds.

The static down force of the strings is proportional to the string break angle over the bridge. That was reduced as much as possible and still remain playable.[9] By raising the tailpiece, 4° was achieved. (See FIG.s 2 and 3.) A minor detail: the fingerboard and original bridge were radiused while the tailpiece was flat across. That gave the outer strings a smaller break angle than the others. To get them to sit properly, the bridge radius was reduced to about half-way to flat from the original. That worked and gave the $\sim 4^\circ$ for all strings and nearly equal action for both aluminum and paper cones.

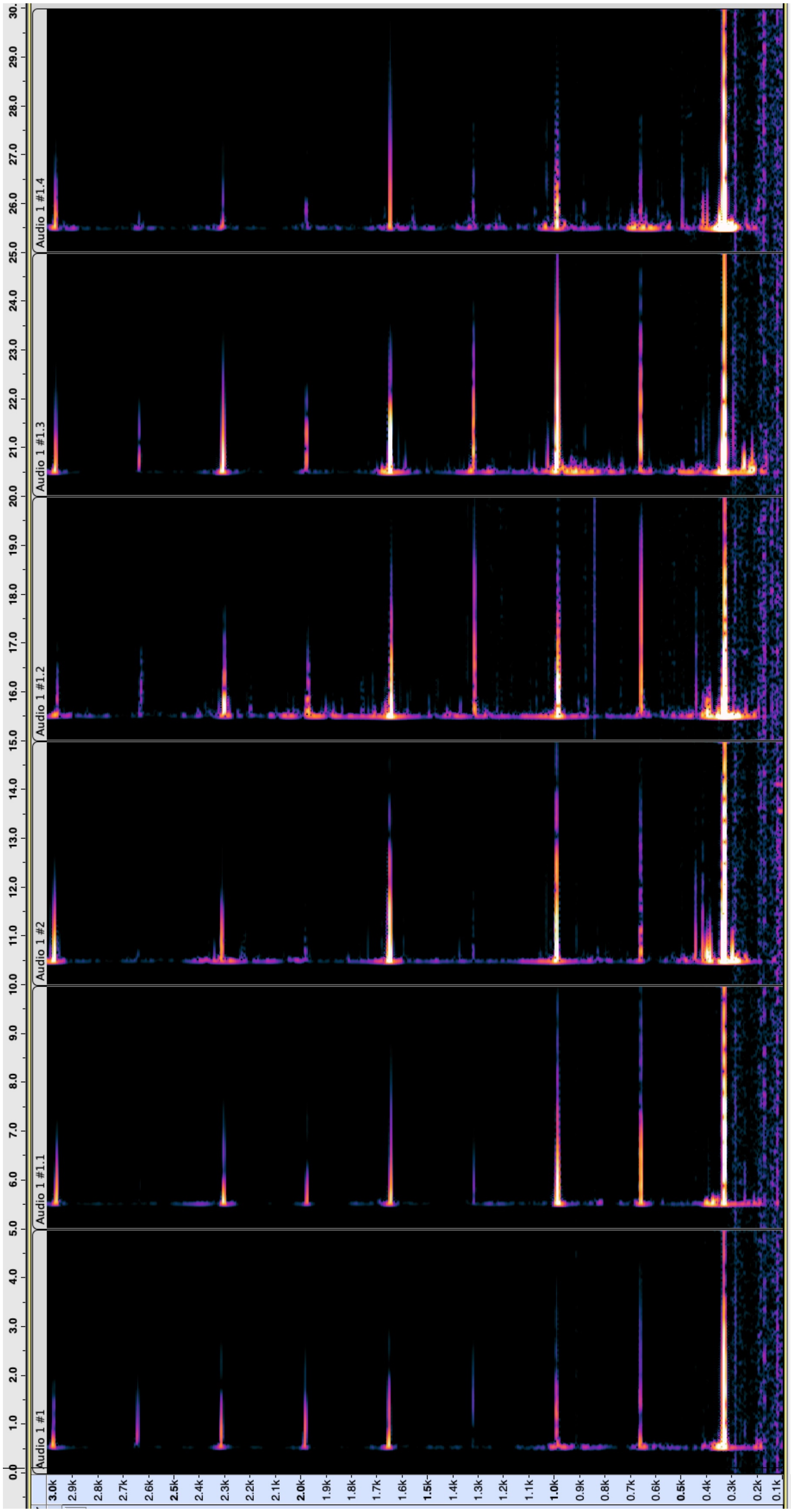
A paper cone has an inherent problem. Unlike aluminum, which can retain its shape under stress and even flex and still be within its elastic limit, paper will deform under constant stress. The 100 lb cardstock held up for repeated recording sessions, but the strings were loosened in between. It would eventually sag if left tuned up.

On a lark, I also tried a PETE #1 take-out food container lid. (It was just the right size.) The PETE lid was essentially flat and could not support the down-pressure of the strings. With an empty cat food can between the lid and the biscuit, the lid bottomed out and rested on the "neck stick" (an extension of the neck that continues through the body all the way to the tailpiece — see FIG. 2). The resulting action was rather high, and the break angle increased to about $6\frac{1}{2}^\circ$. Refinement seemed unwarranted.

2. instruments

The flat-top guitars are both modest price instruments with solid spruce tops and laminated sides and backs. Their body shapes and bracing are different. The steel resonator is a National Reso-Phonic Raw Steel 14-fret. The installed aluminum cone was made by Mike Replogle (https://www.repogleresos.com/). The alternative paper cone and PETE lid were installed in the National, and the original cover grill was attached over them. All three used the same biscuit and bridge (i.e., with the reduced radius). The other resonator guitar was a relatively inexpensive, 14-fret, brass body biscuit/single cone.

Appendix C: larger version of FIG. 6 image of single pluck spectrograms, with two flat-tops at the bottom & the four resonators above


Audio 1 #1
Audio 1 #1.1
Audio 1 #2
Audio 1 #1.2
Audio 1 #1.3
Audio 1 #1.4
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
23.0
24.0
25.0
26.0
27.0
28.0
29.0
30.
3.0k
2.9k
2.8k
2.7k
2.6k
2.5k
2.4k
2.3k
2.2k
2.1k
2.0k
1.9k
1.8k
1.7k
1.6k
1.5k
1.4k
1.3k
1.2k
1.1k
1.0k
0.9k
0.8k
0.7k
0.6k
0.5k
0.4k
0.3k
0.2k
0.1k

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[1] Physical descriptions and histories of resonator guitars can be found in many places. Brief versions are provided in D. Politzer, *Resonator Guitar: Banjo-like Preliminary Plan*, HDP: 22 – 03; https://www.its.caltech.edu/∼politzer/resonator/resonator.pdf, D. Politzer, *An Investigation of Resonator Guitar Sound*, HDP: 23 – 01, https://www.its.caltech.edu/∼politzer/resonato-guitar/resonator-guitar.pdf. The main purpose of those papers is to introduce the question of resonator guitar physics and make sound comparisons, including ones with an instrument with an aluminum resonator cone but no resonating body.

[2] Jim Woodhouse has a still-growing resource on the science of musical instruments: https://euphonics.org. Mostly, it is about the physics, but Chapter 10 has a lot of practical information about doing measurements. There's plenty of good advice, with explanations of pros and cons.

[3] a technical exposition is available, open-access, as *Acoustics of the Banjo: measurements and sound synthesis & theoretical and numerical modeling*, J. Woodhouse, D. Politzer, and H. Mansour, Acta Acustica, **5**, 15 and 16 (2021) https://doi.org/10.1051/aacus/2021009 and https://doi.org/10.1051/aacus/2021008); *Pickers' Guide to* Acoustics of the Banjo, D. Politzer, J. Woodhouse, and H. Mansour, HDP: 21 – 01, http://www.its.caltech.edu/∼politzer – APRIL 2021 is an informal account of some of the salient results.

[4] E. Skudrzyk, *The mean-value method of predicting the dynamic-response of complex vibrators*, Journal of the Acoustical Society of America, **67** 4 (1980) 1105-1135.

[5] D.Politzer, *An Elementary Account of Plucked String Clonk*, HDP: 21 - 03, http://www.its.caltech.edu/∼politzer/clonk/clonk.pdf.

[6] Some builders and players opt for aluminum cones with pressed-in spiral ridges. These make the cones even stiffer while allowing them to be even lighter and move more easily.

[7] The second paper of ref. [1] graphs the response of an instrument with an aluminum cone for its soundboard and no additional resonant body, i.e., shown in FIG. 7, and successfully matches its peak frequency to measurements of the cone weight and static return force to better than 4%.

[8] J. Chowning, *The Synthesis of Complex Audio Spectra by Means of Frequency Modulation*, J. Audio Eng. Soc. 21, 7, 1973.

[9] Break angle physics is explained in ref. [3] and D. Politzer, *Arithmetic of Spring Forces on the Banjo Bridge*, HDP: 21 - 04, http://www.its.caltech.edu/∼politzer/head-stiffness/head-stiffness.pdf. I have never encountered another correct explanation of the physics. The angle certainly impacts the sound in ways familiar to careful listeners. A playable banjo with 0° break angle was constructed and described in D. Politzer, , HDP: 19 - 01, https://www.its.caltech.edu/∼politzer/zero-break/zero-break.pdf (with theory corrected in D. Politzer, , HDP: 20 - 01, https://www.its.caltech.edu/∼politzer/parametric.pdf. Zero break angle guitars have also been constructed.