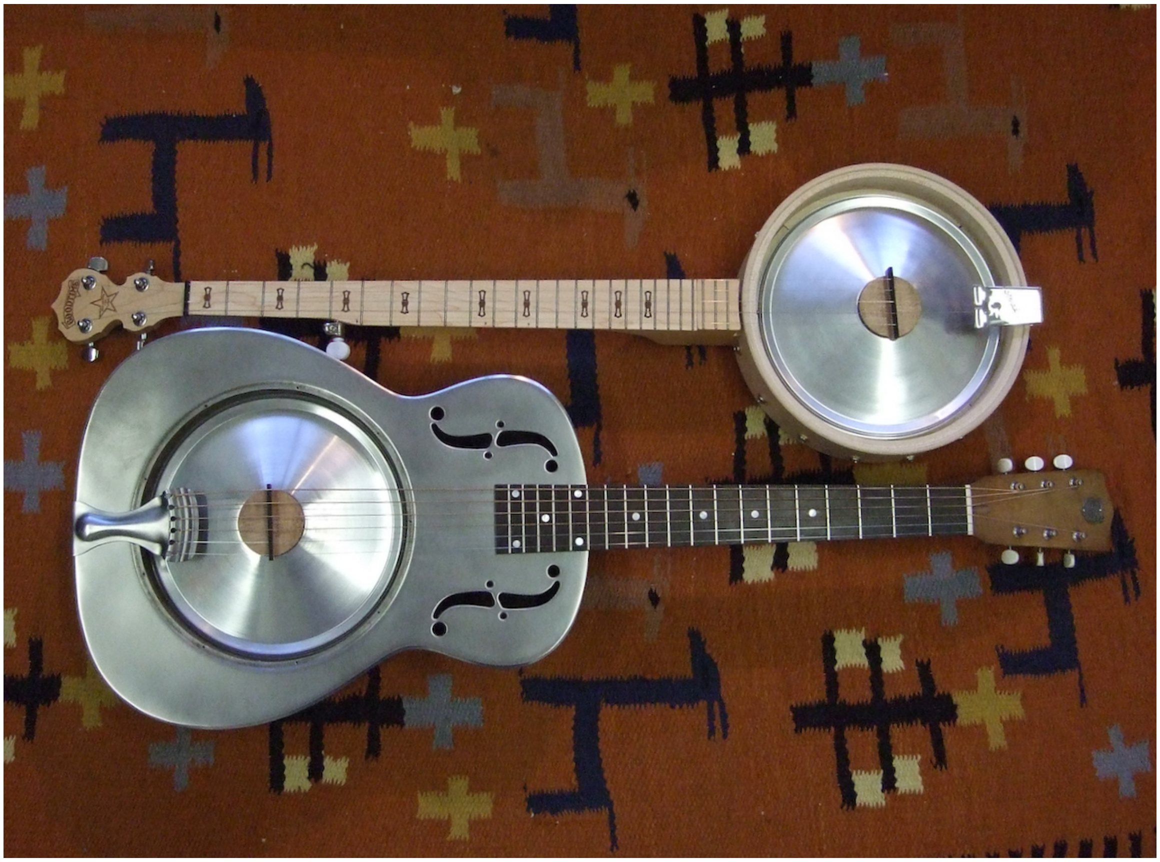

An Investigation of Resonator Guitar Sound

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Identified by the cones that transduce string vibration, resonator guitars have a sound quite distinct from the rest of acoustic guitars. Sound processing by the body is crucial. To illustrate that, a standard single-cone resonator is compared to two design variants, to a banjo, and to a flat-top wood guitar. Similarly played and recorded music is presented for reference. Likely candidates for signatures of the metallic sound are identified in spectrograms and spectra. Almost all of the discussion is descriptive. The only quantitative measurement and calculation relate static physical measurements to the observed main resonance of a cone.

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An Investigation of Resonator Guitar Sound

I. INTRODUCTION

Compared to wood-topped acoustic guitars, resonator guitars stand out as something rather different. First marketed in 1927, they were invented to increase unamplified loudness. Since then, their unique sound has kept them as the instrument of choice for many players — long after the challenge of loudness became moot. The common element of all resonator guitars is a very thin aluminum cone or cones, looking much like paper speaker cones. String vibrations produce cone vibrations which transduce the string motion into sound. In standard designs, the cone sits in a "sound well" which separates the top of the cone and the air above it from the back and air behind it. The former radiates some sound directly, but much of that is blocked by a protective grill. The air disturbance created by the back of the resonator cone excites the air inside the body. This, in turn, produces sound radiation from the sound holes and from vibrations of the body's top. This body sound is much of what the listener hears. Wood-topped guitars and banjos are quite different. For those instruments, most of the sound comes directly off the soundboard (i.e., guitar top and banjo head). And the only dramatic body effect is the Helmholtz resonance, whose frequency is determined by the body volume and sound hole size. This is typically the lowest frequency resonance of the body, and it couples strongly to the sound board and radiates relatively efficiently.

The single-cone resonator guitar was historically the second resonator design. It is chosen here for its simplicity. Cones differ by maker, and people have preferences. This study features cones by Mike Replogle, https://www.replogleresos.com. They have a smooth surface. In contrast, Nationals feature spiral ridges, stamped into the spun cone, as in Fig. 15.

When we identify a particular instrument by its characteristic sound, our brains do many things at once and use many features of the sound to make that identification. Sound synthesis combined with listening tests can be a powerful tool to identify what aspects of instruments' sounds are most important in making those identifications. As no such investigations are currently available for resonator guitars, this preliminary exploration looks at a variety of measures. The obvious choices are spectra and spectrograms. For each of these, different choices of frequency scale and time/frequency resolution might be more or less effective at revealing distinctions that are relevant to our brains. For spectrograms, there is a further choice of how intensity is mapped onto color and brightness. For plucked strings, waveform envelopes also contribute to identifiable differences between instruments.

In this note, I have chosen analyses of recordings which feature qualitative differences in the sounds of the particular five instruments. The implication is that they are generic to the whole class of each of those instruments and relevant to our perception of the different instruments' timbre.

II. OUTLINE

For orientation, section §IV contains a musical selection played and recorded five times, as similarly as possible. First is an open-back banjo. Next is a banjo-like instrument where the head has been replaced by a resonator cone. The next two are the same single-cone resonator guitar, without and then with the protective grill over the cone. And finally, for comparison, the selection is played on a wood-topped acoustic guitar. These are the five instruments that are compared throughout.

Section §V gives a more detailed description of the instruments.

Section §VI presents a "poor man's" version of point admittance measurements of a string forcing the bridge on each of the five instruments. Admittance is the velocity of the bridge divided by the applied force of the vibrating string at their point of contact. This is the first step in the conversion of string motion to sound. And the "poor man" uses near-field sound recording as an unnormalized surrogate for explicit bridge motion sensing.

The sounds of open strings plucked at the 12^{th} fret are compared in section §VII. Attention is paid both to amplitude variations over extended frequency intervals and to the detailed structure of narrow peaks that accompany the string harmonics but are not themselves in harmonic integer ratios. Tailstrings damped and undamped are compared.

Section §VIII presents the static measurements that determine the cone primary resonance. In the violin and banjo families, this admittance enhancement is known as the bridge hill.

A summary and some conclusions are offered in section §IX.

Appendix §A gives a *very* brief description of the design and history of the three main resonator guitar variants. Appendix §B is a reflection on materials and the "sound" of aluminum. Appendix §C is a technical note on the choice of the 12^{th} fret for location of the single plucks.

III. YOUR JOB

As you listen and peruse the calculated graphical representations, what differences stand out? How would you characterize them? Are they interesting and/or important? What might be their origin?

IV. PLAYED MUSIC EXAMPLES

This study is structured as a comparison of the sound of five different instruments. The underlying questions include: How does the cone mounted in a banjo rim differ from the same frame with a typical banjo head and bridge? How is resonator cone sound modified by placing it in a guitar body? How is that further complicated by covering the cone with a grill? Finally, how does the resonator guitar compare to a wood-topped acoustic guitar?

Even if the sounds of some of these instruments are familiar, they are typically used in different genres of music and by different players. To focus on what is different about the instruments themselves, I play the same musical bit with the same technique on each. The one compromise is that the two 5-string instruments are tuned and picked like banjos and the three 6-string instruments like guitars.

The recordings used the same equipment and the same configuration of player, microphone, and room. All are plucked with bare fingers, with an effort to use the same force. The instruments naturally produce sound at very different volumes, as quantified by carefully controlled single plucks presented in sections §VI and VII. To focus on timbre, I adjusted the playback volumes of this musical bit to be roughly equal. Rather than use the same strings tuned to the same pitches and played identically, I chose the instruments' natural tunings and typical strings. The two 5-string instruments are set up like banjos and tuned in double-C (gCGCD). The three 6-string instruments are tuned to drop-D (DADGBE). Audacity's software was used to raise the 5-string recordings from the key of C to D. (The obvious alternatives, i.e., tuning the strings higher or capoing at the send fret, have subtle impacts on the voice of the instrument. For possible use in future analysis, the original 5-string recordings in C are also available in the folder given below.)

In this single mp3, the instruments appear in the following order: banjo, resonator cone mounted in a 5-string open-back banjo rim, resonator guitar with grill removed, resonator guitar (including grill), and flat-top acoustic guitar:
http://www.its.caltech.edu/∼politzer/resonator-guitar/resonator-mp3s/all-5-pitch-loudness-adjusted.mp3 (The five separate recordings as well as the original 5-strings in C are in http://www.its.caltech.edu/∼politzer/resonator-guitar/resonator-mp3s/ .)

V. THE INSTRUMENTS

A banjo was re-purposed to study the sound of a cone by itself, without the additional complication of the resonant hollow body.[2] Photos are on page 1 and in Fig. 1. For this comparison, not only the cone but also the bridge and biscuit set in the banjo rim are the same Replogle models as are installed on the resonator guitar shown on page 1.

The resonator guitar is a Raw Steel 14 fret by National Reso-Phonic Guitars, with a steel body. As normally played, the cone is protected by a covering grill and the bridge by a bridge guard. (See Fig. 2.) The grill impacts the the sound, altering the balance of direct cone-top sound and body sound.

Fig. 3 is a sketch of a cross section of the full assembly, drawn through the middle of the bridge.

To place these resonator-cone instruments in the world of acoustic, plucked, string instruments, the comparisons include a banjo and a guitar. The guitar is a 6 Spruce by Simon & Patrick, a division of Godin. It has a solid spruce top and plywood sides and back.

Inadvertently, over the course of these investigations, banjos were re-purposed, and different banjos were used in the recordings. Within a given set of comparisons, the same recording set-up was used for each instrument, as that was deemed more relevant that resurrecting the previous banjo. The banjos were sufficiently similar to each other and sufficiently different from the other instruments that re-doing the earlier recording sessions seemed unnecessary. All three banjos were Deering open backs. They differ in wood species and tailpieces.

FIG. 1: banjo mounted resonator cone

VI. THE SOUND OF CONTROLLED WIRE-BREAK PLUCKS AT THE BRIDGE WITH DAMPED STRINGS

Thin copper magnet wire wrapped around a string will break at essentially the same tension every time. The exact position along the string, which determines its initial har-

FIG. 2: resonator guitar with grill and bridge guard installed

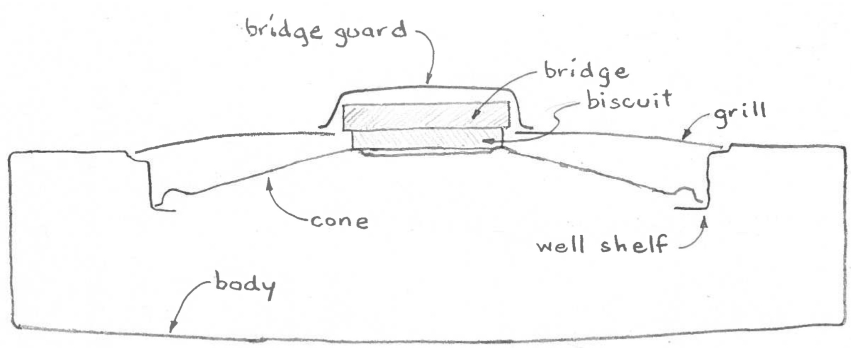

FIG. 3: single-cone (& biscuit) resonator guitar cross section – to scale

monic content, is also repeatable with precision. Thus, wire-breaks offer a pluck of a given force and position that can be applied multiple times to the same or to different different instruments.[3] The recordings presented here include a poor man's version of string force admittance at the bridge. The actual sounds of plucks at 4′ from the front of the body of the instruments are presented in the next section. Both were done only on the 1st string.

The 1st string diameters were 0.010″, 0.009″, 0.012″, and 0.011" for the banjos, banjo-resonator, resonator guitar, and wood-topped guitar, respectively.

Different recording volumes and wire gauges were used in different situations to optimize the digital recording because of the variation in instrument output for a given force of pluck.

The magnet wire varied from 0.0018″D #45 to 0.0040″D #38. For the comparisons, the breaking force is then assumed to be proportional to the cross sectional area.

The set-up for the string breaks at the bridge is shown in Fig. 4. The strings are damped, and the mini condenser microphone is placed as close to the bridge as possible without touching.

Repeating string breaks on the same instrument produces observable differences in the recordings. However, they are tiny compared to the differences between instruments. Hence, a convenient comparison can be made using just one typical pluck recording for each instrument. The following recording and figures present such plucks for the five instruments. The order is banjo, resonator cone in the banjo rim, resonator guitar with protective grill and bridge guard removed, resonator guitar with grill but no bridge guard, and acoustic guitar.

These are the sounds of the five plucks, scaled to represent the same force of pluck and same recording volume: http://www.its.caltech.edu/∼politzer/resonator-guitar/Goodtimebanjo-banjores-resun-rescov-guit-same-force-same-percent.mp3

(This is an uncompressed version of the file linked above for download for anyone interested in the minute details: http://www.its.caltech.edu/∼politzer/resonator-guitar/Goodtimebanjo-banjores-resun-rescov-guit-same-force-same-percent.wav)

Fig. 5 displays the wave forms and spectrograms of those five plucks. 0.40 seconds of recording time are displayed for each one, and the spectrogram uses a linear frequency scale, running from 0 to 2000 Hz.

Computed spectra of the five plucks are displayed in Fig. 6 and 7. Fig. 7 uses the same data as Fig. 6 but employs a four-times lower frequency resolution. Also, the successive plucks are offset by 20 dB for visibility.

To repeat: use your ears and eyes. The strings are all damped. The 1st string is plucked right at the bridge. And the recorded sound is purported to be a surrogate for the motion of the bridge directly below it. So, these are measures of how the bridge moves in response to string motion. Controlling pluck strength and position of pluck and microphone produces results that can be compared directly among the five instruments — even if the absolute, common normalization in the proper units of admittance (velocity/force or time/mass) is not known.

FIG. 4: National resonator with Replogle bridge, biscuit, & cone, damped strings, and mini condenser USB mic, with the protective grill and bridge guard removed

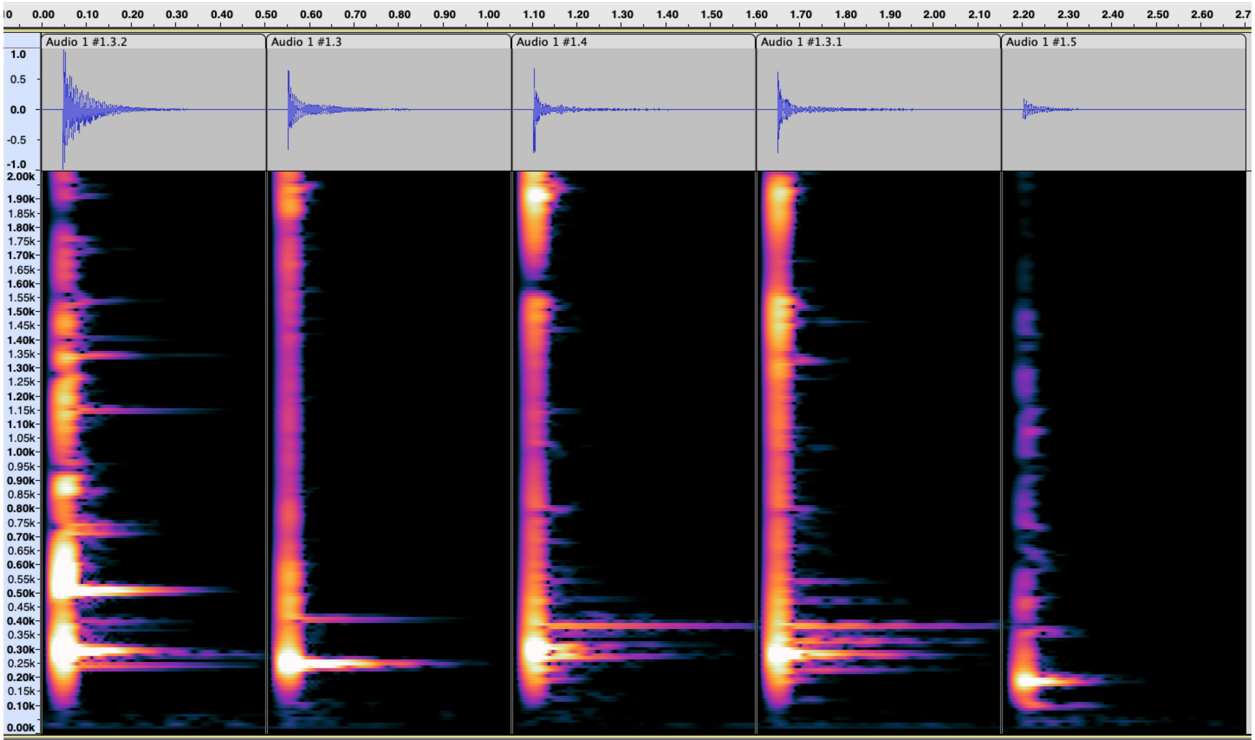

FIG. 5: wave forms and spectrograms of the five damped-string plucks at the bridge

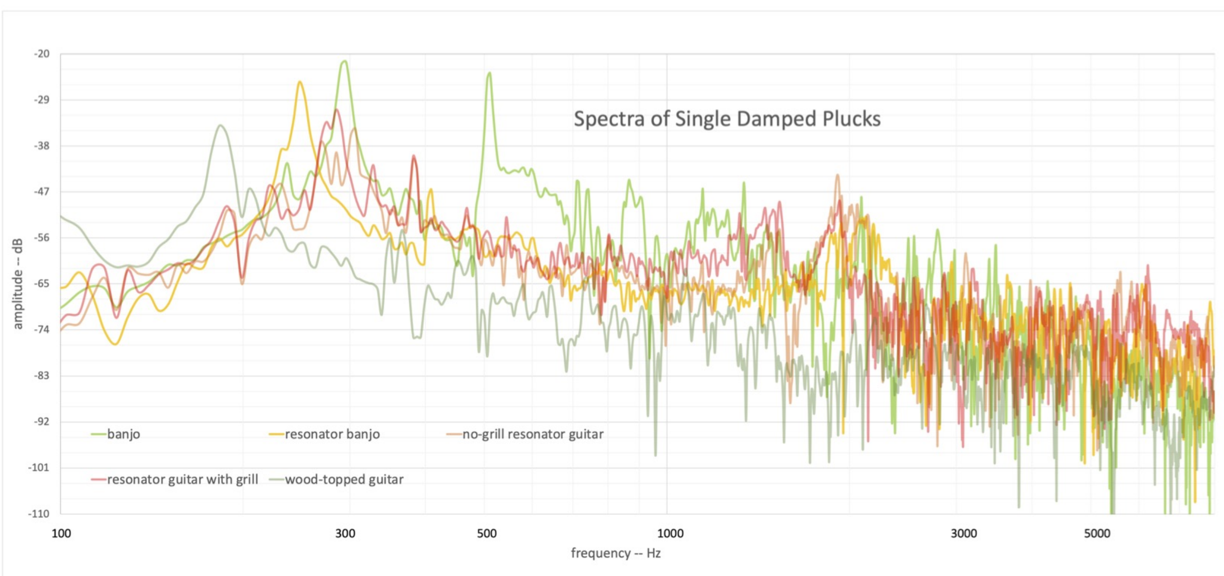

FIG. 6: spectra of the five damped-string plucks at the lowest resolution that represents actual individual peaks

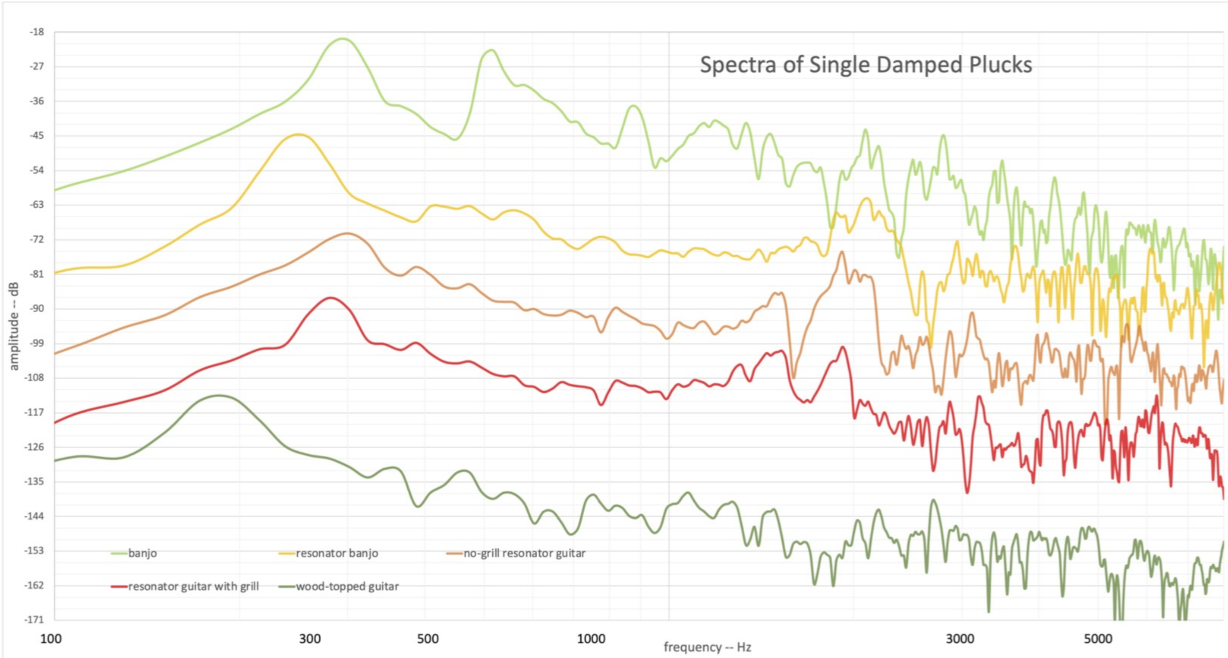

FIG. 7: spectra of the five damped-string plucks at four times lower resolution and successively offset by 20 dB

VII. OPEN STRING PLUCK SOUNDS AT 4′

With all strings open in gCGCE (open-C) and DADGBE tunings, the 1st string was plucked with a wire break at the 12th fret, i.e., in the middle. With a pluck in the middle, the string's initial form has zero amplitude for even harmonics, and amplitudes of odd harmonics are proportional to $1/n^2$. (See Appendix C for further information and rationale.)

The following mp3 and uncompressed wav are recordings from a microphone 4′ away, and Fig. 8 is a display of the waveforms and spectrograms.

http://www.its.caltech.edu/∼politzer/resonator-guitar/Vegabanjo-banjores-resun-rescov-guitar-undamped.mp3

http://www.its.caltech.edu/∼politzer/resonator-guitar/Vegabanjo-banjores-resun-rescov-guitar-undamped.wav

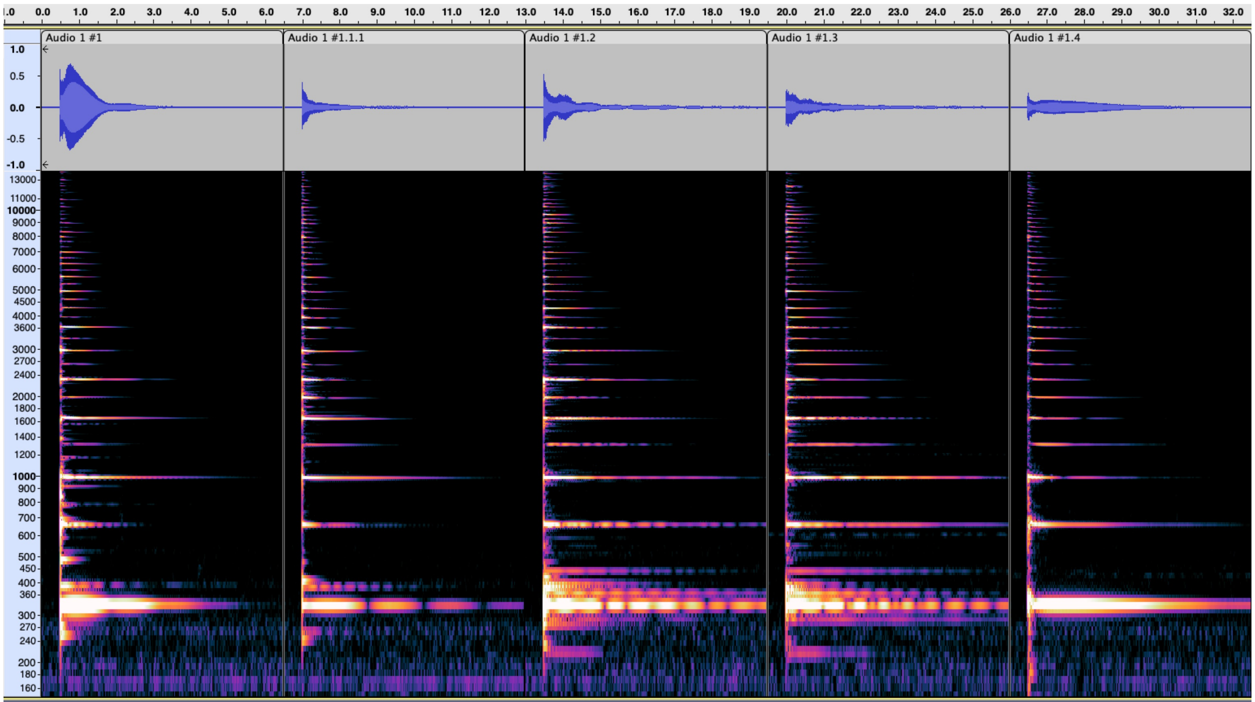

FIG. 8: wave forms and spectrograms of the five mid-string plucks – no strings damped

A. tailstrings?

The tailstrings were not damped on any of the instruments in the plucks given above. One might question whether they are responsible for the well-defined spectrogram peaks that are not plucked-string harmonics. Their length relative to the scale length is 0.115. The open 1st was tuned to E(3) = 330 Hz. So, the fundamental of the 1st tailstring was 2870 Hz, i.e., beyond the graphed region. However, some harmonics of the other five strings are in the plotted frequency range.

Fig. 9 gives a comparison of the resonator guitar with the cone grill cover installed and 1st string plucked at the 12th fret with all tailstrings damped and undamped. The same prominent anharmonic features appear in both spectrograms. In the spectrum plot, the undamped case shows only one weak peak around 975 Hz and a very weak one around 1240 Hz that do not match peaks in the damped case.

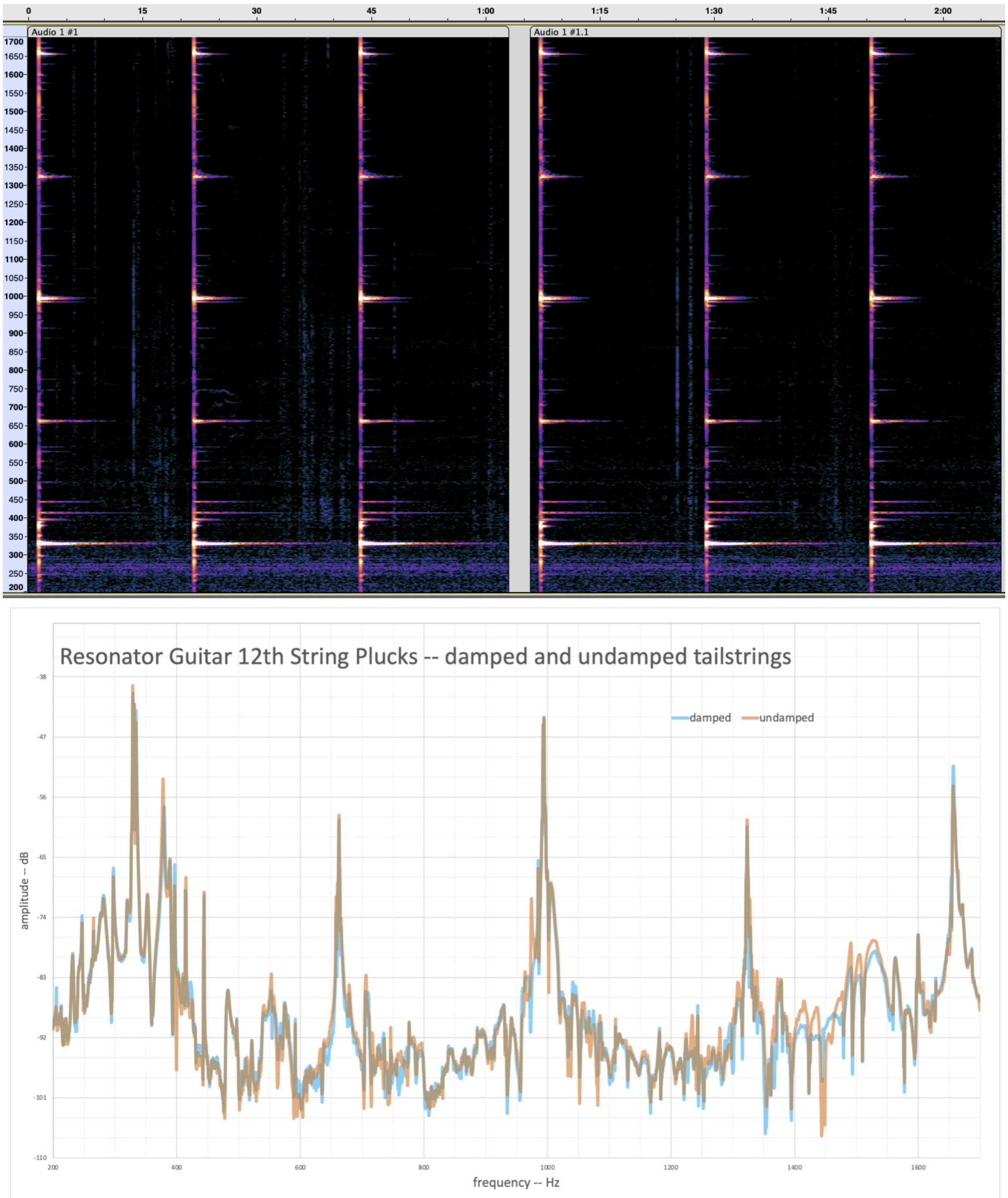

FIG. 9: spectrogram and spectra for plucks on the resonator guitar with cone cover grill and all tailstrings damped on the left and undamped on the right

B. a closer look at some fine-scale structure

The sound of a plucked string certainly includes contributions from the other strings. Some of this is sympathetic vibration, forced by the plucked strings. And some comes from the modes of the other strings that are excited by the initial, sudden disturbance of the pluck. The effects of the other strings are easy to identify by comparing to damping the un-plucked strings. However, of interest to the present investigation is what remains of the pluck sound.

In the following, all strings were damped except for the 1st. In addition, all tailstrings, including the 1st, were also damped.

Listen to the five instruments: http://www.its.caltech.edu/∼politzer/resonator-guitar/goodtime-banjores-uncovered-covered-guitar-1st-only-12th-fret-all-damped-but-1.mp3

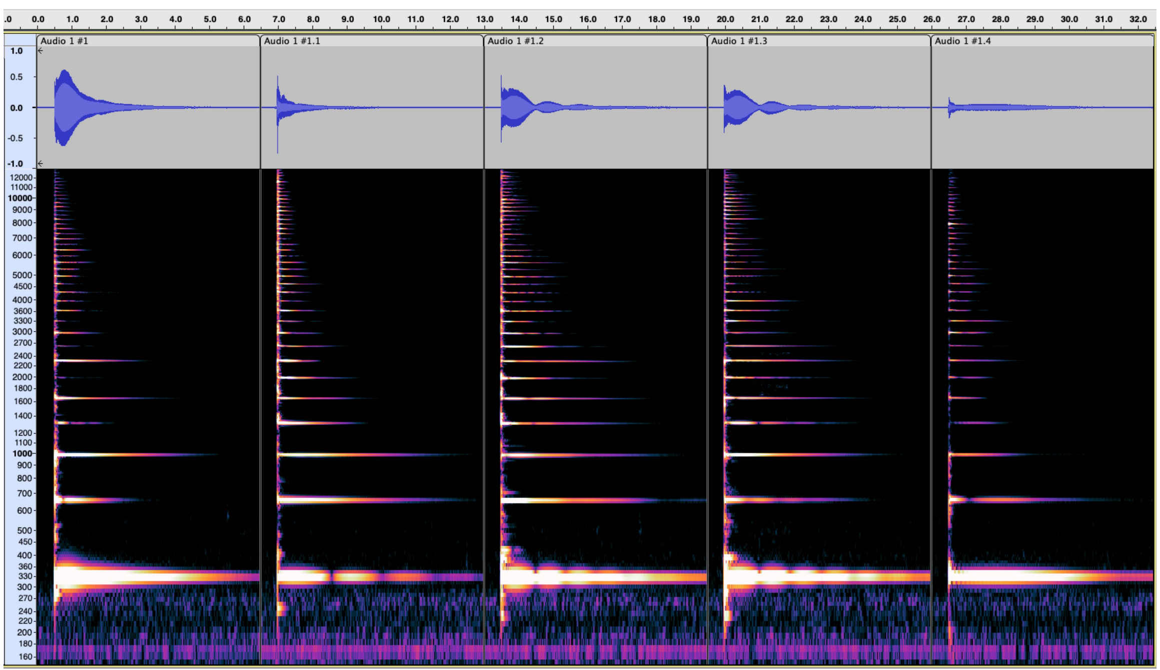

FIG. 10: 1st string pluck at 12th fret, tailstrings & all other strings damped, mic at 4′

Fig. 10 shows waveforms and spectrograms of these plucks. Fig. 11 gives spectrograms with finer detail, displaying only 200 to 1350 Hz and 1 sec duration. (The abrupt cut at 1 sec produces a signal in the Fourier analysis; those signals' width in time reflect the time resolution that accompanies the choice of frequency resolution.) And Fig. 12 shows the spectra computed for the initial 0.10 sec of each pluck.

The anharmonic features that are well-defined in frequency are presumably resonances of the instruments' bodies.

(A simple reminder: In normal playing, there are usually more than one pluck per second — and often several more.)

Fig. 13 is simply an example from another recording session – in all its glory. In particular, it is the resonator guitar with its grill cover and all strings open.

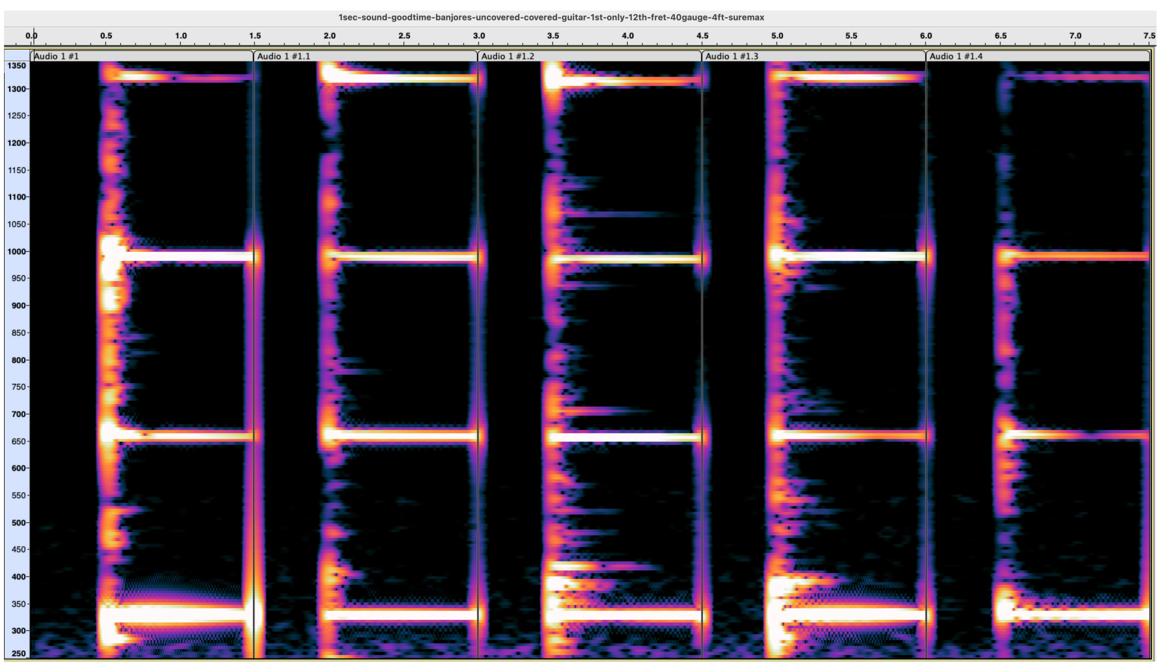

FIG. 11: 1st string pluck at 12th fret, tailstrings & all other strings damped, mic at 4′

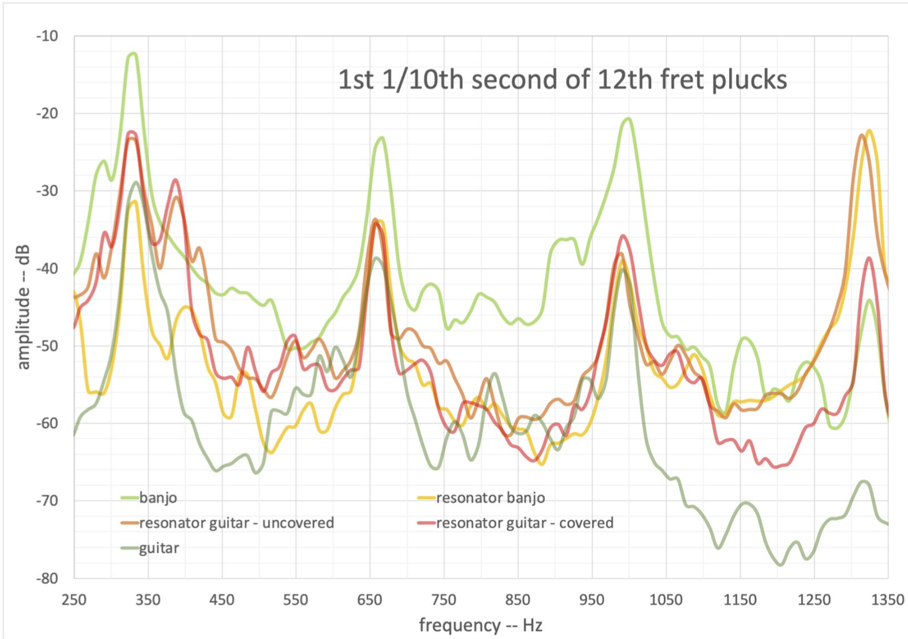

FIG. 12: 1st string pluck at 12th fret, tailstrings & all other strings damped, mic at 4′

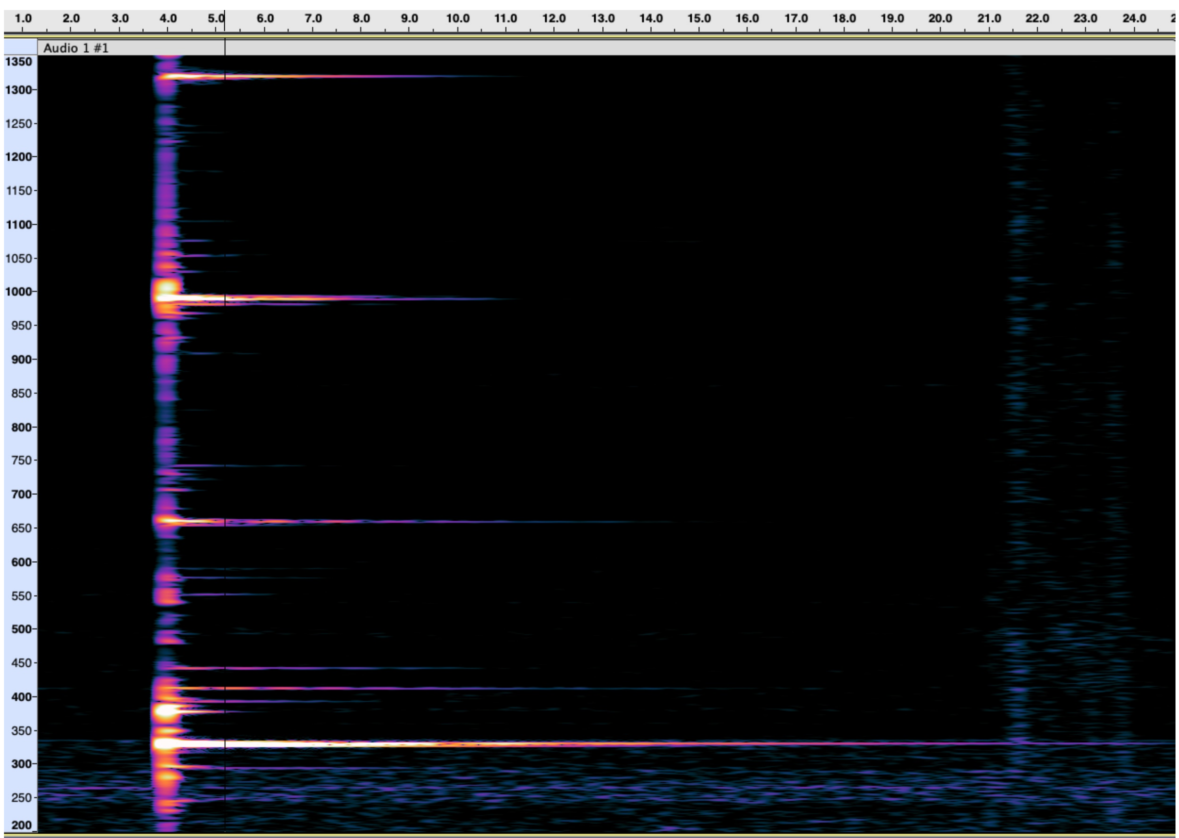

FIG. 13: `covered resonator guitar, all open strings, pluck at 12th fret, mic at` 4′

VIII. THE BISCUIT HILL

A. formant context

The bridges and bodies of acoustic string instruments together produce formants that impact their voice. The bridge hills are prominent features in the violin family and in banjos. A simple sketch of the physics goes as follows. The bridge and the material below it form a simple oscillator. Its mass is that of the bridge and that material. The restoring force is the sum of the strings pushing down and the material structure pushing up. These two balance at equilibrium and exert a restoring force, back towards the equilibrium position, when the bridge is displaced. String vibration initiates a resonant response in this oscillator near its natural frequency. That resonant oscillation decays via production of waves in the soundboard, which, in turn, produce sound in the air. In wood-topped instruments, there is substantial dissipation in the wood. In membrane-topped instruments, most of the dissipation is energy lost to outgoing sound. In both cases, the bridge oscillator loses energy quickly. Hence, its spectrum is broad in frequency. Its impact is to enhance sound production in the region of its resonant frequency, encompassing many string overtones, relative to sound production at other frequencies.

B. the cone IS a speaker!

The resonator cone doesn't simply resemble a speaker cone, it actually is constructed and functions in much the same way. Both are forced by a central disk of substantial diameter. Although fixed at the very edge, both cones have a relatively flexible outer ring that allows a piston-like motion for their lowest mode of vibration. On an audio speaker, that part is sometimes called a "rubber surround." The conical shape adds stiffness that allows that nearly rigid, piston-like motion. Higher frequency modes impact performance characteristics that influence the choice of one design over another. Of course, the desiderata in guitars and speakers are very different. Bare aluminum is sometimes used for speakers, but it is generally recognized as having too little damping. That leads to more sharply-defined and longer-lived resonances — which sound "metallic." There are coatings that provide the aluminum with more acceptable damping. The outer flexible bellows ring on a resonator cone is formed by four 90° bends followed by an upward 15° bend to form the conical surface. When one pushes down on the biscuit, the bellows function becomes obvious. The whole cone appears to move down as a single, rigid object. Note that the eight feet of the spider bridge in Fig. 16 sit on the edge of the movable "piston" and not on the fixed, very outer edge of the cone.

C. static measurements & determination of the fundamental spear resonance

The static restoring force of the combination of strings and cone can be measured directly. Weights placed on the bridge produce a displacement. Using the resonator cone/banjo rim instrument, the displacement was measured with a dial gauge from below. The results are plotted in Fig. 15. The seemingly odd choices of units are those of the measurement devices themselves. The straight line fit yields an inverse slope of 9.8×10^4 N/m. While the actual motion produced by plucked strings is in the range of the lowest couple points and below, the straight line model is a plausible extrapolation down through that region.

For a reasonable estimate of the relevant mass for this oscillator, I take the total weight of the bridge, biscuit, and cone and subtract an estimate of the weight of the flexible bellows region at the edge. The final estimate is 0.040 kg, which gives an estimate of 249 Hz for the frequency.

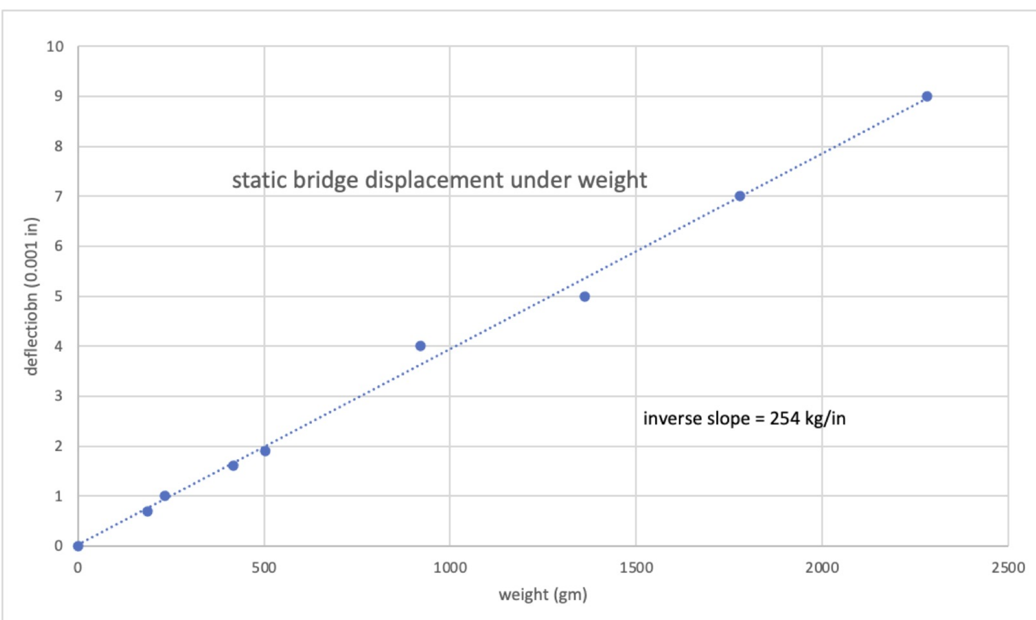

FIG. 14: measurements of static bridge displacement on the resonator banjo

Motion of the cone at the biscuit hill resonant frequency necessarily includes some further flexing at intermediate radii, even though there are no node lines. Slight flexing at that resonant frequency would reduce the effective mass from the total mass value and raise the frequency above 249 Hz when viewed as a simple oscillator. An estimate would require far more sophisticated apparatus and/or calculation than used here.

The spectra of near-field sound recordings at the bridge on the 1^{st} string are shown in Fig.s 6 and 7. For the resonator banjo (whose return force is plotted in Fig. 15), a strong formant is evident in Fig. 7 and is centered at 259 Hz. The strength and width depend on the coupling of the biscuit hill oscillator to the string and to the waves in the cone. Estimating these is beyond the scope of the present effort.

The peak frequencies for the two versions of the resonator guitar are slightly higher. This is to be expected because the greater number and heavier gauge of the strings make a larger contribution to the return force than the strings of the resonator banjo. Furthermore, the uncovered version strings have a slightly larger break angle over the bridge than uncovered. That is because the cover supports (and damps) the tailpiece from below.

All three versions involving the resonator cone reveal enhancement of possible interest between 1500 and 2000 Hz. In the banjo, the lowest frequency formant corresponds to motion of the bridge as a whole, while the next higher two are associated with two particular bridge flexing modes. Something analogous is likely here. For audio speakers, the appearance of these higher resonances is called "breakup."

IX. SUMMARY & CONCLUSIONS

The ambitious, long-term goal is to connect physical properties of resonator guitars to their characteristic sound. Both sides of this connection present challenges. The physics is complicated by two features. The two-dimensional surface that transduces string vibration to sound is not the direct source of most of the sound we hear. And the rest of the guitar is a complicated structure. On the listening side, it is not immediately obvious what quantifiable aspects of the sound dominate our impressions.

A proper speaker is ideally linear in its response. Filter and cross-over circuits use speaker cones where they are best-behaved. In contrast, the shortcomings of aluminum for speaker cones are likely important for resonator cone sound: they have less damping than paper. So, aluminum has more sustain and more prominent resonances.

The resonator cone broad admittance peak centered around 300 Hz is simple to understand in terms of static measurements. With that central frequency, it is effective at transducing the string fundamental frequencies, and that is essential for a guitar-like sound.

Regarding our impressions of the sound relative to wood-topped guitars, lighter weight and less damping make resonator guitars louder and more prominent at high frequencies.

Even banjos with no metal parts are said to “ring.” Much of this timbre is due to the anharmonic resonances of the head that are excited by sudden plucks. The harmonic string modes die off with comparable decay times because of the efficiency of sound radiation. The resonator cone histograms presented here show lots of power in sharply defined, long lived peaks at frequencies that are not in the strings’ harmonic series. John Chowning’s initial discovery of the utility of frequency modulation to synthesize metallic sounds pointed to the induced FM sidebands as the source of the timbre.[4] Resonator guitars have lots of thin metal parts. But which one does what and how they are connected and excited remain to be explored. The displayed spectrograms each involve a choice of frequency/time resolution and choices of mapping the recorded amplitudes onto color and intensity. Very different choices could look rather different. In general, spectrograms capture more of what we hear in a pluck sound than would a spectrum of the complete time evolution. For a given frequency component, we certainly care about the initial amplitude and the time to decay below some threshold. The spectrogram choices I made emphasize features that I believe are important for perception.

The obvious open questions are, as stated above, which component does what and how they are connected.

Appendix A: VERY brief history and design of resonator guitars

The history of resonator guitars is a tangle of inventions, partnerships, patent infringements, and buy-outs.[5] It played out in Southern California in the 1920’s and early ’30’s and produced the three common configurations of resonator guitars as well as the first mass-produced electric guitars. The key figures were John Dopyera, George Beauchamp, and Adolph Rickenbacker, who hailed from Slovakia, Texas, and Switzerland, respectively, and whose contributions were primarily as inventor, musician & promoter, and fabricator, respectively.

The first commercial design was the tri-cone, where the bridge activates three separate

6″ cones. Cost of production prompted the introduction of a simpler model — like the one studied here. Disagreements led to formation of a new company, and dispute over the ownership of the single-cone patent produced the inverted cone with the spider bridge.

These remain in mass production to this day, nearly 100 years later, with designs very close to the originals. Variations are now produced by individuals and small producers.

FIG. 15: tri-cone configuration

FIG. 16: spider bridge and cone

Appendix B: a reflection on materials and the "sound" of aluminum

Martin & Co.'s X series offers instruments that they advertise as "durable and affordable without sacrificing tone." The indestructible necks are roughly 25-ply. Sides and back are "HPL" ("High Pressure Laminate," something quite akin to the Formica® used for kitchen counters; if it looks like wood, it's an image in the plastic and not veneer.) The pricier X series tops are wood, but the base model tops are HPL.

FIG. 17: Martin Alt-X aluminum & HPL (High Pressure Laminate) guitar

For a time, they built ones with brushed aluminum tops. (See Fig. 17.) They were visually suggestive of the original German silver resonator guitars. However, they sounded just like the corresponding all-HPL models and nothing like resonators. There is nothing metallic about their sound.[6] The aluminum models were short-lived because the glue used to attach the bridge and bracing often failed.

The Martin Alt guitars are impervious to weather and relatively inexpensive. They do not sound Great. However, I am not certain that the materials are to blame. For all of history, production of musical instruments has been overwhelming based on making units that look like ones that are deemed to sound good. In contrast, the evolution of designs is driven by the sound and not the appearance. Swapping materials but retaining structural dimensions necessarily alters the sound — most likely for the worse. Density and internal damping clearly impact the response of a guitar top. Reproducing the sound of solid wood without altering the instrument's design dimensions would require careful matching of the new material's properties to 1/8″ spruce. Hardest to match are the spruce's stiffness characteristics. Spruce is highly anisotropic, in stark contrast to the obvious examples of laminate or aluminum. These days, there are examples of synthetic material fabricated to match the anisotropies of natural ones. Légère plastic reeds for woodwinds are examples. They are *expensive*. If you don't match material physical properties, you have to invest in extensive R&D to consider design alternatives.

The aluminum of a resonator cone is very thin. That gives it larger amplitude vibrations and louder consequent sound in response to the force of the strings than heavier thin wood. However, it would not be strong enough to serve as the top of an acoustic guitar. On the other hand, very thin steel has been used as the head of a banjo.[7] It is very loud. But tension rather than inherent stiffness is the primary restoring force. So, it sounds like a banjo.[1]

For reference, here are some relevant material physical parameters for comparison. The values are for typical banjo head mylar, the aluminum cones, and 1/8″ spruce, and they are listed in that order: banjo, resonator guitar cone, and wood-topped guitar.

mass per unit volume: 1.7 , 2.7 , 0.45 g/cm^3

thickness: 0.02 , 0.02 , 0.3 cm

surface density: 0.03 , 0.06 , 0.14 g/cm^2

Young's modulus: 5 , 70, 10 GPa

Energy dissipation is a more complicated issue. On a banjo, most of the energy put into the head by the strings is converted into sound. Internal dissipation into heat is a minor effect.[1] This may also be true for the resonator cone. For soundboard wood, it is certainly the opposite, giving the particular material's internal friction a crucial impact on the sound.

Appendix C: the initial plucked string spectrum

Ideally, for a pluck at the 12$^{\text{th}}$ fret, all string modes with nodes at that point, i.e., the even numbered ones, are not excited. The amplitudes of the odd ones are proportional to $1/n^2$, where n is the mode number. On a log-log plot, e.g., amplitude in dB *vs.* log frequency, this is a straight line. Plucking anywhere else introduces an initial amplitude modulation of the string itself by weakening modes with nodes near the pluck to the extent that they are near. Attention must be paid to not confuse this modulation with something of a different origin. For example, the equal temperament 17^{th} fret divides the string at $2^{-17/12} \approx 0.37458$ times its length. That is quite near 3/8 and also somewhat near 1/3 and 2/5. Hence, every 8^{th} mode will be very weak in a pluck at the 17^{th} fret. Every 3^{rd} and 5^{th} mode will also be relatively weak, although to a lesser extent. Plucks at the 12^{th} fret have a distinctive sound of their own, but they do not introduce modulations over frequency from the initial string configuration that might look like bridge or body formants.

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[1] 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.

[2] https://www.its.caltech.edu/∼politzer/resonator/resonator.pdf, HDP: 22 – 03, *Resonator Guitar: Banjo-like Preliminary Plan*

[3] 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.

[4] J. Chowning, *The Synthesis of Complex Audio Spectra by Means of Frequency Modulation,* Journal of The Audio Engineering Society **21** 526-534 (1973); available as https://ccrma.stanford.edu/courses/220a-fall-2015/homework/3/Chowning_FM.pdf . This was the basis of what I believe to be Stanford University's all-time second highest money-making patent.

[5] An attempted definitive account was given in *The History and Artistry of National Resonator Instruments,* by Bob Brozman, CenterStream Pub., Fullerton, CA, paper 1993 (&1998)

[6] A famous case of visual stimuli overwhelming the actual air vibration in the perceived sound is given by the McGurk Effect. See, e.g., https://www.youtube.com/watch?v=G-lN8vWm3m0

[7] Alfred A. Farland was a vitruoso banjo performer and teacher. He designed and patented many banjo features including a thin metal head c.1890. The tension was adjustable using standard hooks and ring. (The banjos were manufactured by Rettberg & Lang.)