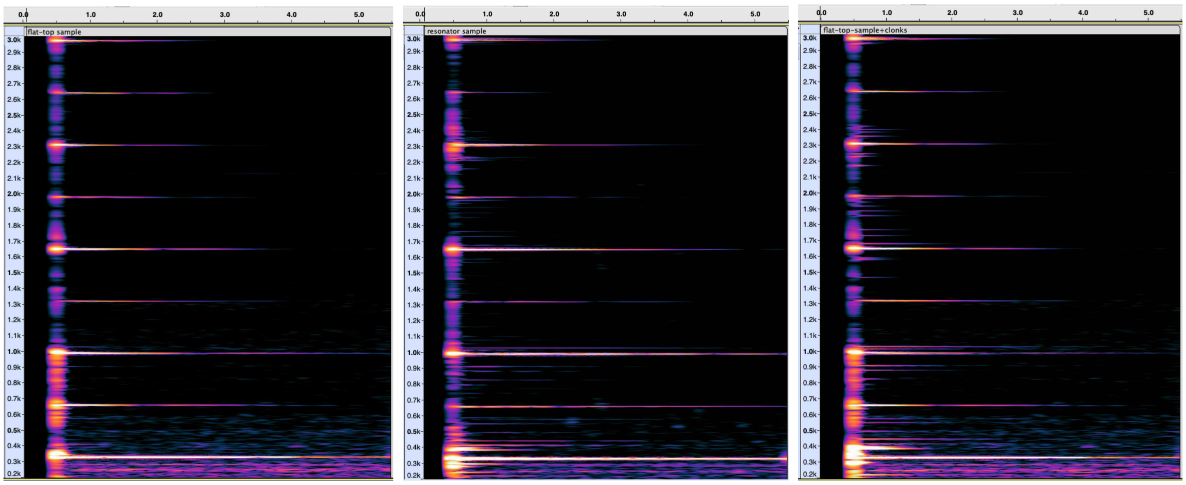

Resonator Guitar Synthesis

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Spectrograms of plucks on resonator guitars reveal frequency components that are weaker and shorter-lived than the string harmonics but are clearly discernible as individual resonances. These are absent or far, far weaker in the sound of acoustic, flat-top guitars. Simple, computer-generated sounds produced from sine waves with frequencies, amplitudes, and decay times that are typical of the non-harmonic resonator guitar sounds are combined with the sound of a flat-top guitar. The resulting sound is linked here. The reader-listener can judge, but it is claimed that the combination definitely falls into the category of resonator guitar sound. The synthesized sound on its own, i.e., without any flat-top pluck sounds and amplified sufficiently to be heard clearly, is rather like that of a noisy gong.

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I. INTRODUCTION

People who care can easily distinguish the sound of resonator guitars from the more common types of acoustic guitars. The common ones of various shapes and designs all have tops that serve as soundboards, which transduce string vibration into air vibration. On resonator guitars, one or three very thin aluminum cones transfer string motion to the air. In fact, the cones need not be aluminum or even very thin, but they do have to be sufficiently light that they produce substantially more air vibration than standard soundboards. That makes the resonator guitars louder than other types, and that was the original intent. However, even adjusting for loudness, the resonators' timbre is distinct. The questions at hand are: 1) What in the sound allows that identification? And 2) what in the physics of the instruments produces that characteristic sound?

The spectrograms of a small selection of flat-top and resonator guitars pointed to a possible answer to question #1.[1] The present effort is an attempt to confirm that identification. A tentative answer to question #2 is discussed in section §VI, but an explicit demonstration will require further work.

II. DISTINCTIONS IN THE SPECTROGRAMS

Ref. [1] studied six instruments. Two were modest flat-top, steel string guitars, with solid spruce tops and laminated sides and backs. Not surprisingly, with different body designs, they sounded different from each other. Of the four single biscuit resonator guitars, one was a modest brass-bodied instrument. The other was a quality steel-bodied instrument which was played first with a proper aluminum cone and then with two radical cone substitutes. One substitute was a stiff cardstock cone, designed to function much like the aluminum one. The other was a flat disk of thin plastic. These four certainly sounded different from each other.

Both with played music samples and with the sound of single, well-controlled plucks, it was easy distinguish flat-top from resonator and even easy to identify which instrument was which. Spectrograms of the single plucks showed a feature common to all the resonator guitars and absent from the flat-tops.

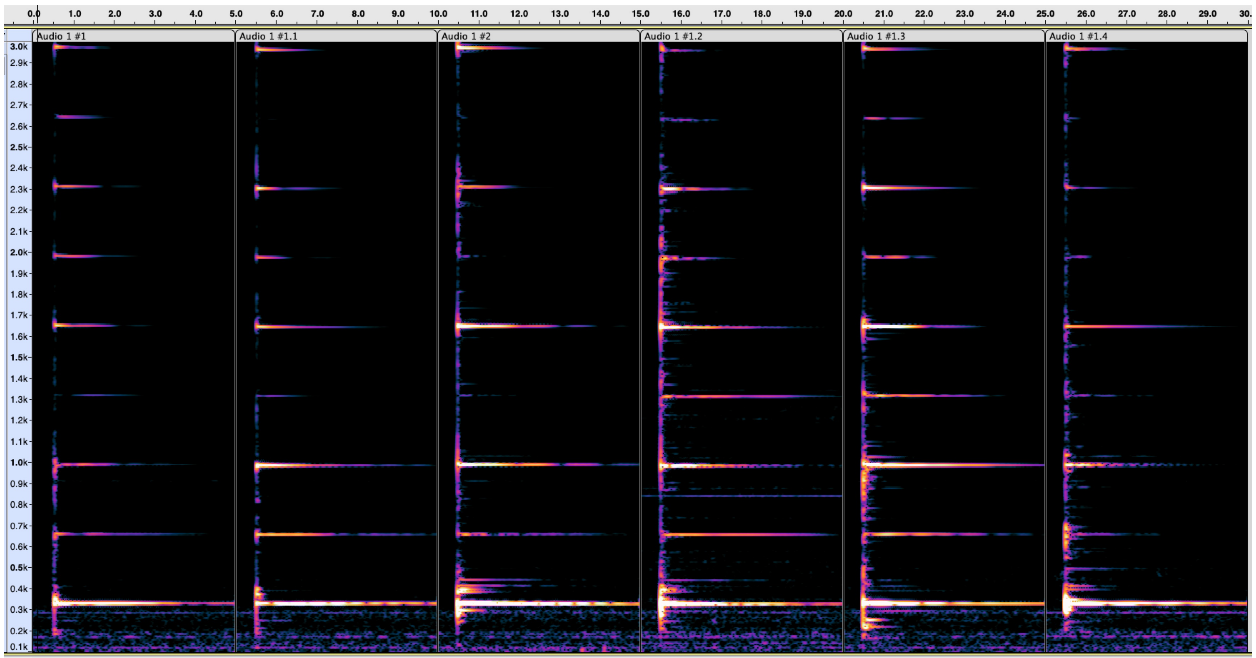

FIG. 1: 1st string plucks at the 12th fret on each instrument: two flat-tops on the left and four resonators on the right; relative loudness as produced by identical plucks on identical strings (from ref. [1])

FIG. 1 shows a spectrogram representation of each of the six plucks. (Uniformity of the plucks in terms of location, direction, and strength is explained and demonstrated in ref. [1]; FIG. 1 displays just one representative pluck per instrument, but the variations from one pluck to the next on a particular instrument were negligible compared the the differences between instruments.) Each recording is 5.0 seconds long. The displayed frequency range is 0 to 3000 Hz. The feature common to all resonators and absent from the flat-tops occurs over the whole audible frequency range but 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.

For the present investigation, new recordings were made of 1st string plucks at the 12th fret on one of the flat-tops and on the brass-body resonator (with its standard-style cone). FIG. 2 shows their spectrograms. In this case, the flat-top sound is amplified by 5dB to get overall loudness comparable to that of the resonator.

Here is a [volume-adjusted] reminder that the two guitars sound quite different when

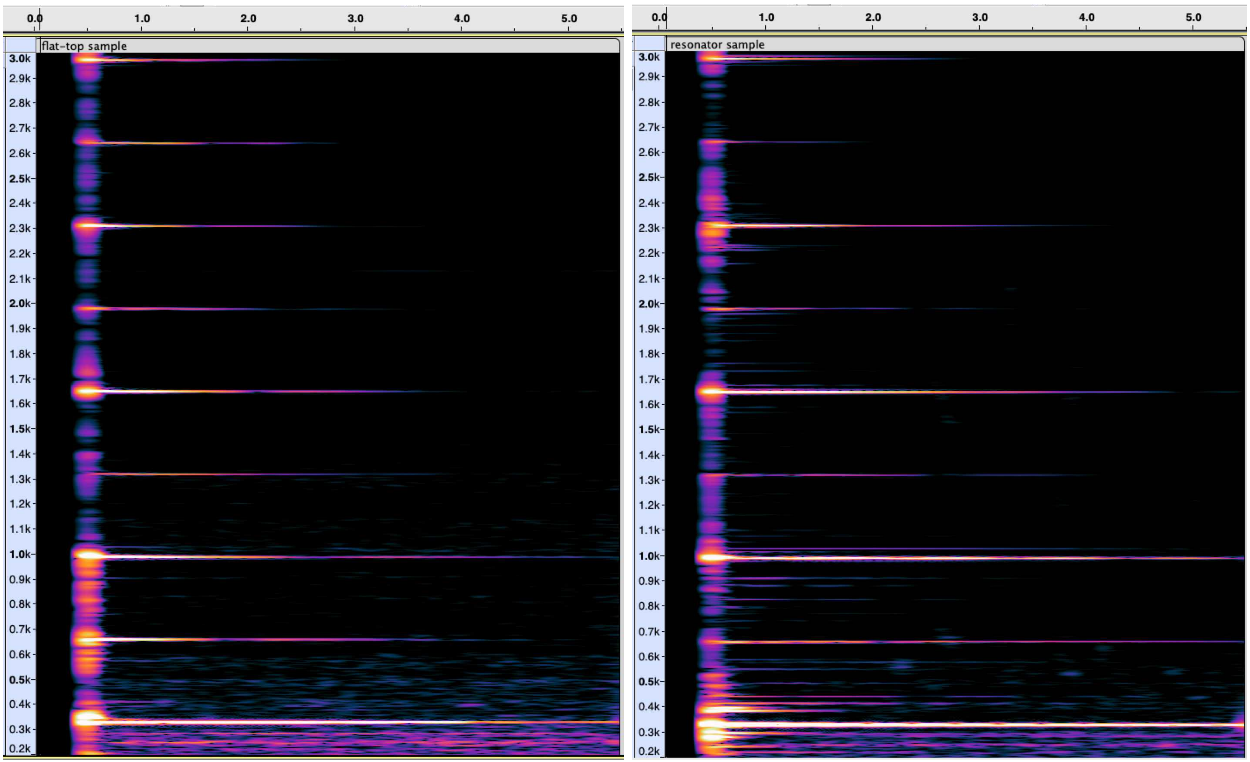

FIG. 2: 1^{st} string plucks at the 12^{th} fret on each instrument: flat-top (loudness adjusted) on the left and resonator on the right

played — first, the flat-top, amplified by 5dB, and then the resonator. Longer selections are included in ref. [1].

http://www.its.caltech.edu/∼politzer/paper-cone/KC-sp+5dB-then-royall.mp3

III. SYNTHESIS OF THE "EXTRA" RESONATOR SOUND

To understand the role of the persistent spectrogram features of resonator guitars that are absent from flat-tops, a large set of simple sounds was generated, i.e., using Mathematica. Each simple sound was constructed to produce a spectrogram like one of the weak "extra" ones of the resonators. They were then all merged into a single sound file. That file was then merged with the sound of a flat-top pluck. By design, this total combination has a resonator-like spectrogram. The crucial point is to listen. Does it sound like a resonator guitar? The sound of the synthesized set by itself is also quite interesting and telling.

A. the form of the single sounds

Each individual synthesized sound was generated as simply as possible. Each begins with a sine function of time with the desired frequency. That sine is multiplied by a slowly varying envelope that includes a brief rise time and a slow exponential decay. Thirty nine frequencies were used for the range of 0 to 3000 Hz. (That's not a magic number, but it did seem to cover the kind of things that appear in the various resonator spectrograms. Since each resonator guitar was different in its particulars, there was no need to reproduce one of them exactly.) When the full set of these were merged, their amplitudes were adjusted to mimic what appears for the resonator guitars.

Note that a spectrum or spectrogram does not include phase information. They only reflect amplitudes of Fourier components. Relative phases can radically effect the totality of a sound, especially if there are many frequencies close together. The extreme example is white noise *versus* a single clap. These can have the same spectra.

In terms of symbols, each individual sound looks like

$$f(t) = A\ \mathrm{e}^{-t/\tau}\ \tan^{-1}(t/\rho)\ \sin(2\pi\nu t)$$

where ν is the frequency, τ is the decay time, ρ is the rise time, and A is the amplitude chosen to produce in the end a typical spectrogram.

For example, this is the sound for $\nu = 331$ Hz, the pitch of the plucked 1^{st} strings, with a decay time comparable to actual plucks and a relatively gentle rise time:

http://www.its.caltech.edu/∼politzer/pluck-synthesis/331Hz-sine-pluck.mp3

and this is the wave form or, more realistically, the chosen envelope (because the 331 Hz sinusoidal variation is too rapid to show on this scale):

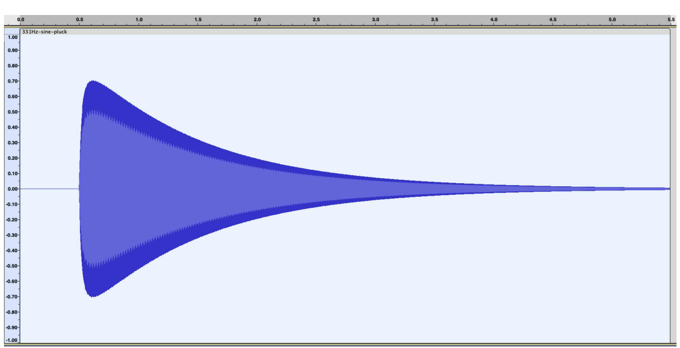

FIG. 3: a Mathematica-generated sound file for a 331 Hz sound as described above

IV. ADDING 39 SOUNDS TO THE FLAT-TOP GUITAR

The result of adding the thirty nine sinusoidal sounds to the flat-top guitar pluck is shown on page 1 and repeated in FIG. 4.

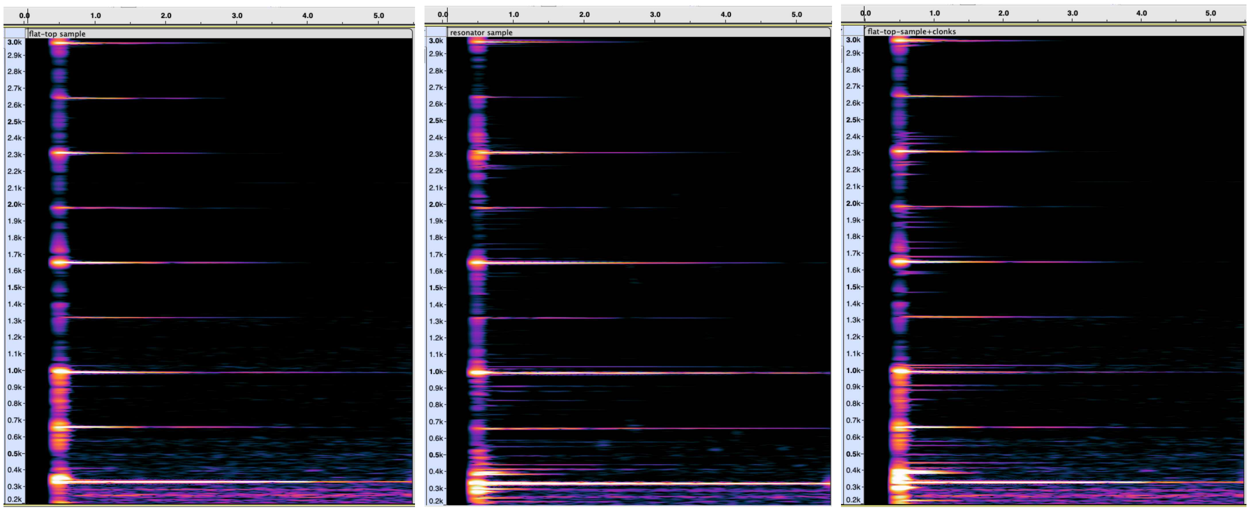

FIG. 4: flat-top, resonator, and flat-top PLUS 39 sine waves; 5 sec recordings; 200 to 3k Hz

The resemblance of the synthesized spectrogram to the set of resonator spectrograms in FIG. 1 is clear — and by design. The crucial issue is what it sounds like. Here are the sounds of the single plucks, first the flat-top, then the resonator, and then the flat-top with the thirty nine added sine waves:

Flat-top: http://www.its.caltech.edu/∼politzer/pluck-synthesis/flat-top-sample.mp3

Resonator guitar: http://www.its.caltech.edu/∼politzer/pluck-synthesis/resonator-sample.mp3

Flat-top + synthesized sounds: http://www.its.caltech.edu/∼politzer/pluck-synthesis/flat-top-sample+clonks-combined.mp3

A. comments on beating

In some instances, a note on a string instrument can exhibit beats, i.e., a periodic loud-soft modulation of the volume. In the particular examples chosen, this is evident for the resonator guitar pluck and not the flat-top. Because the bulk of the synthesized sound is built upon the flat-top sound, there is no prominent beating in that sound either. To be sure, beating is more common in resonators than flat-tops, but it certainly can appear in the latter — particularly with the lower notes. In all cases, the origin of these beats is well-understood, including why they are more pronounced on the resonators.

The physics of these beats goes as follows.[2] Every string resonance is actual two resonances, corresponding to two possible transverse wave polarizations. Ideally, these two have exactly the same frequency. Several factors can split this degeneracy. The most common is motion at either of the string ends, which is almost certainly not symmetric with respect to the polarizations. The result is two nearly equal string frequencies, which, when sounded together, produce the beats. The perceived beat frequency is simply the difference of the frequencies of the two strongest components of the total sound.

Resonators were invented to have more motion at the bridge than is produced on flat-tops. (They're louder.) So, audible beats are more common. Some beating is discernible in the "extra" sounds themselves. (Listen below in section §V.) But one only hears that clearly in the absence of the much louder flat-top string sound.

V. THE 39 SOUNDS ON THEIR OWN

The sound of the thirty nine extra files is actually quite satisfying in the context of this project. Here they are, without the flat-top string pluck. Their relative amplitudes are exactly as indicated in the spectrogram, but the overall amplitude is boosted to make it easier to hear:

http://www.its.caltech.edu/∼politzer/pluck-synthesis/all-clonks-combined.mp3

VI. PHYSICAL ORIGIN OF THE "EXTRA" SOUNDS

The sudden disturbance produced by a pluck has the potential to excite all of the resonances of the instrument body. The initial amplitudes of those excitations depend on how the ends of the plucked string couple to those body and/or air motions. These resonances then decay with their own characteristic frequencies and decay times.

A minimal, simple model of this phenomenon is worked out in detail in ref. [3]. Considered there is a single damped harmonic oscillator subjected to a sinusoidal force that begins abruptly at $t = 0$ and then continues indefinitely. The consequent motion of the oscillator is the sum of two parts. One part is a persistent oscillation at the driving force frequency whose amplitude and relative phase are determined by the driving force. The other part is a free exponential decay at the oscillator's natural frequency, with the decay time determined by the oscillator's own damping. The amplitude and phase of this part of the motion are determined by having the total initial amplitude and velocity match whatever initial conditions are required.

Perhaps the most interesting lesson from this model is how the free-decay amplitude depends on the forcing frequency. Not surprisingly, the amplitude is biggest when the driving frequency is near the natural frequency. Not initially obvious is that a given driving frequency is roughly equally effective at exciting the oscillator for all natural frequencies below the driving frequency but increasingly ineffective for driving free decays with frequencies higher than the drive.

In the present case, this suggests that body motions excited by the onset of string modes are most noticeable at lower body frequencies. In the resonator guitar spectrograms, almost all prominent "extras" occur below 3000 Hz.

VII. CLANG *VS* CLONK

The case of the distinction of resonator guitar sound from flat-top sound appears to be one where a matter of degree becomes a matter of kind. Tap a wood flat-top guitar or any other traditional wood-bodied string instrument in a variety of places, and it will produce a variety of thuds or clonks. Each body has its own damped resonances, and different tap locations couple to the various resonances with different strengths. However, all those resonances are very short-lived compared to the lifetime of a pluck. The resonator guitar considered here has a metal body – likewise the three others considered in ref. [1]. Many tap locations can produce sounds with much longer lifetimes. A single long-lived resonance is not sufficient to sound "metallic." There must be several components, and they must not be simply related in their frequencies. Note that even banjos with no metal parts are said to "ring." Presumably, that is because of a significant presence of sound components that are not simply related to the plucked string pitches. A wood or woodblock sound does not have a great many oscillations before it dies away.

The excitation of these "extra" frequencies must be sufficiently strong for their sound to be apparent in a pluck sound. The sensitivity of our hearing and experience with sounds of musical instruments and other objects apparently make it possible to discern sound components that are quite weak relative to the "musical" ones. But there certainly must be a level below which they go unnoticed. Apparently, the light resonator cone or cone substitute, essentially mounted inside the body, is relatively very effective at exciting body modes.

VIII. 39?

As mentioned, 39 was not a magic number. Rather, it covered the "extras" that appeared in actual resonator guitar spectrograms below 3000 Hz that did not appear or were far weaker for the flat tops. For convenience, they were constructed in intervals, i.e., 5 between 200 and 350 Hz, 8 between 350 and 600 Hz, 6 between 600 and 1300 Hz, 11 between 1400 and 2000 Hz, and 9 between 2000 and 3000 Hz, but there was no special significance to those groupings. By themselves and amplified for easy listening, the set of the lowest 5 sound rather like a resonant drum. On their own, each of the other four groups sound like some sort of metal object struck by a hammer. However, when amplitude-adjusted to be combined with the flat-top sound, the highest 20 extras, i.e., from 1400 to 3000 Hz, were so soft that their sound could easily be missed in the total.

FIG. 5 shows the spectrograms of the five arbitrary groupings of extra sounds, and this is what they each sound like:

http://www.its.caltech.edu/∼politzer/pluck-synthesis/clonks-ALL-SEQUENTIAL.mp3

Each of the five sets has been auto-scaled separately so that the maximum amplitude in of each set is as big as possible without distortion — likewise in FIG. 5.

A. metallic sound?

A single sine wave sound is given in section §IIIA. Two sine waves beat at their difference frequency. Three sine waves with odd frequency ratios, especially if their decay times decrease with increasing frequency, already hint at a metallic sound.

There clearly will be a continuum in making a distinction between resonator guitar and flat-top sound, and it will depend on the listener where to make the cut. The examples presented so far have been chosen to be clear to almost any casual listener.

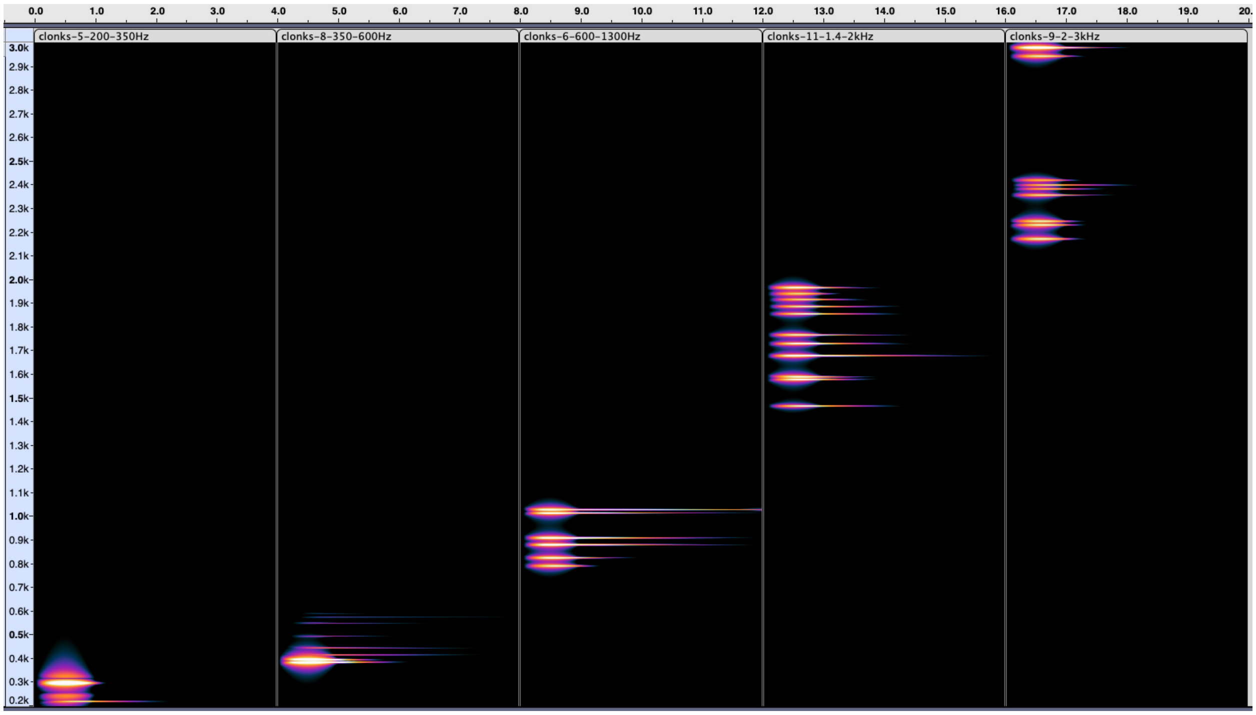

FIG. 5: spectrograms of the five sets of damped sine waves that play in the sound selection above

IX. THE OBVIOUS NEXT QUESTION

The previous study illustrated a fact known to many players and builders: the resonator cone need not be metal or even a cone. It can still produce the sound of a resonator guitar if it is appropriately light. The obvious next question is: how do the sounds of wood-body resonator guitars compare. They were first built by the Dopyera brothers when they set out on their own, having left the original National String Instrument Corporation. They did not have capital on hand to buy the necessary metal tooling. Some players embraced the new instruments, as they were somewhat mellower than the original metal Nationals but still distinctly resonators. Wood-body resonators certainly have some resonator twang and are the choice of many players to this day.

The details are left to future study.

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[1] D. Politzer, *Resonator Guitar Physics Clue from a Paper Cone*, HDP: 23 - 03, http://www.its.caltech.edu/~politzer/paper-cone/paper-cone.pdf.

[2] D. Politzer, *The plucked string: an example of non-normal dynamics*, American Journal of Physics, Am. J. Phys. **83** (2015) 395 and/or HDP: 14 – 04, https://www.its.caltech.edu/∼politzer/plucked-string-final-411.pdf, *Zany strings and finicky banjo bridges*, HDP: 14 – 05, https://www.its.caltech.edu/∼politzer/zany.pdf

[3] D. Politzer, *An Elementary Account of Plucked String Clonk – a key part of banjo soun*, HDP: 21 – 03, http://www.its.caltech.edu/∼politzer/clonk/clonk.pdf