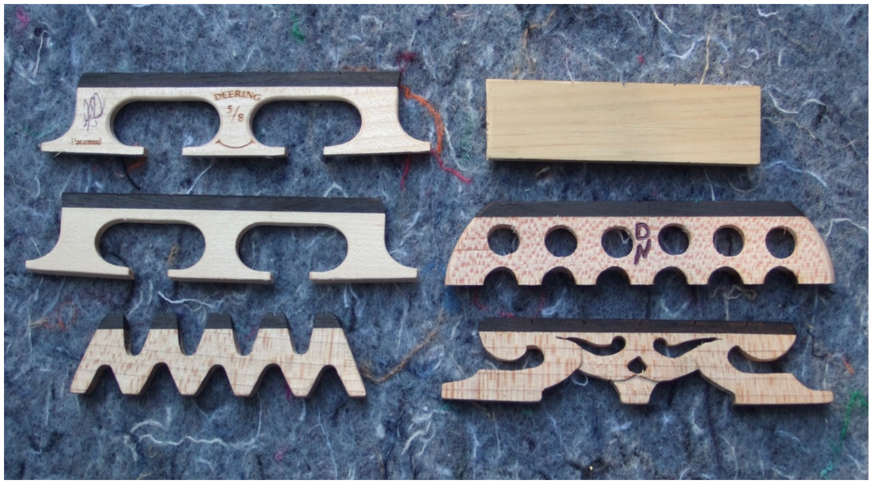

High Frequency Formants from Banjo Bridge Design

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(Dated: February 22, 2021)

Eight bridges, matched for weight and height, reveal some of their secrets. Seven are ebony-topped maple; one is solid poplar. Five have radically different shapes. Two are similarly shaped three-foot bridges with obvious differences in grain. And three differ by the tiniest of wood removal (i.e., less than 0.04 gm).

Below 2 kHz, the bridges perform nearly identically — in accord with the notion that bridge weight and break angle determine the bridge's impact in that frequency region. But at higher frequencies, they impart individual voices. The results are consistent with the idea that the flexing of the bridge plays an essential role in producing the differences. With flexing the key, the same bridge does different things to the sounds of different banjos because the operative flex footprint has to move in conjunction with motion of the head. The crucial additional variables are string and head materials, tensions, and break angles. The three dimensional aspect of flexing is why wood species matters for a given weight and 2D shape. The examples contradict the relevance of a "path" taken by the sound from the strings to the head; that is also dubious from the perspective of basic wave physics.

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I. INTRODUCTION

Using a drum head as the soundboard of an acoustic stringed instrument makes details of the bridge important in ways that have no analogs on wood-topped instruments[1]. Bridge physics is a major contributor to shaping a banjo's "formants," i.e., frequency regions of particularly strong sound production in response to the strings. The formants are a technical characterization of a particular instrument's voice — just as they are an important aspect of people's individual voices. Switching the bridge is likely the simplest and least expensive way to alter a banjo's voice. (Note that the issue is regions of frequency rather than isolated resonances.)

To a good approximation, the main banjo formant, typically centered around 700 Hz for the type of instruments used here, is sensitive only to the bridge mass and break angle. So for this study, I chose to compare bridges all with the same mass and height. Most comparisons are done on a Deering Sierra, which is in the same general category as the instrument studied in ref.[1]. A light open-back built by Colin Vance is used to demonstrate that bridge effects depend strongly on the rest of the banjo. (See more of Vance's work at http://www.vancebanjos.com .)

II. THE BRIDGES

Six of the 5/8″ bridges are pictured on page 1. There is a Greg Deering (signature) "Smile," weight = 2.26 gm. That's the kind of bridge that came with the Eagle II used in ref.[1]. There is a "spillway" bridge made by Don New. The design and Don's handiwork in particular are quite popular. He makes them to all possible dimensions and in all woods (as well as a few other designs). One can find them on eBay and in the classifieds section of the Banjo Hangout (e.g.,
https://www.banjohangout.org/classifieds/search.asp?m=byposter&v=16242).
This spillway weighs 2.24 gm. The up-down-up-down bridge is henceforth labeled "Weitzel" after its creator, Jeff Weitzel. He calls it the "6-10" — six feet and ten legs. It weighs 2.19 gm. Weitzel is a sculptor turned banjo luthier (https://weitzelbanjo.com) in Eugene, OR.

I was idly browsing banjos on-line and stumbled on his fascinating and gorgeous creations. This bridge caught my eye as a possible example of something with very different flex characteristics from the first two. (Flexing was identified in ref.[1] as a crucial part of the two high frequency formants that appeared in that study, i.e., centered around 3.5 kHz and 5 kHz.) And I couldn't resist another one of Weitzel's unusual designs. He says it was inspired by the classic violin bridge. The one in this experiment is 2.28 gm. There is a three-legged Deering Goodtime, weight 2.27 gm. The MSRP is only 40% of the signature Smile bridge. The latter starts with carefully chosen wood and involves more finishing steps in fabrication. A final sound test by Greg Deering identifies those that get the "signature" designation. And there is 2.25 gm rectangular block of poplar.

Sound samples of playing with the spillway and Weitzel 6-10 up-down-up-down on a Deering Sierra are presented in **§V** (page 9). There you can hear the differences identified in FIG. s 4, 5, and 6 below. Playing samples of the Smile bridge and the poplar block on the Vance iOTA are linked in **§IX** on page 23.

III. THE IDEA

The vibrations of a plucked string apply forces to the bridge. The consequent motion of the bridge and head produce sound in the adjoining air. The goal of this study is to characterize the bridge motion produced by particular, well controlled forces.

In ref.[1], bridge motion was studied in two ways. There was computer numerical modeling of the bridge, head, and surrounding air, using state-of-the-art software employed by a vibration analysis professional. And bridge motion was measured on the actual banjo.

The formants identified in the physical measurements, centered at 3.5 and 5 kHz were identified with the calculated bridge/head resonances shown in FIG.s 1 and 2, reproduced here from ref.[1]. For the physical measurements, the bridge was repeatedly struck by a tiny hammer apparatus, designed to be very reproducible. In that experiment, three different geometries were employed for the hammer blow. The resulting motion was recorded by a laser Doppler vibrometer. "Admittance" is the technical measure of motion produced by a given force. The hammer blow is a superposition of (effectively) all frequencies of forcing. And the resulting measured motion is Fourier analyzed into frequency components. Those calculations and measurements are well-beyond the resources available at home in

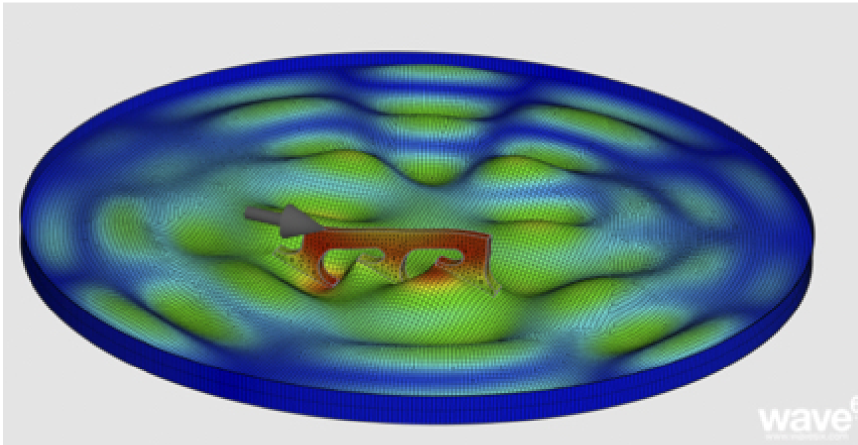

FIG. 1. numerical calculation of resonant bridge/head motion near 3500 Hz.

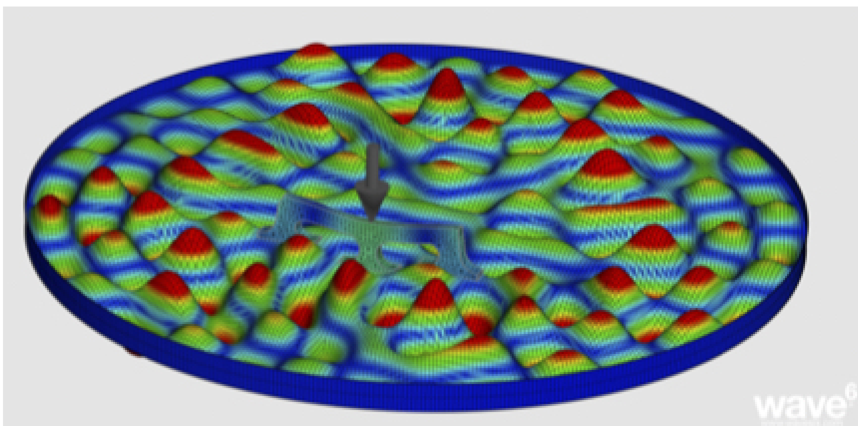

FIG. 2. numerical calculation of resonant bridge/head motion near 5000 Hz.

this safer-at-home era.

A. A bit of physics

As explained in ref. [1], formants arise from the interaction of the bridge with the head. The admittance of the head without strings and bridge is a smooth, gradually rising function of frequency — smooth when averaged over successive individual resonances. The interaction of the bridge with the strings and head adds resonances (normal modes) that were not present without it. Those resonances are very broad, i.e., span frequency intervals that contain many individual head and string resonances because they quickly lose energy to the head and, from there, to sound. (That's elementary physics: stronger damping yields broader resonance.)

Formant is a qualitative concept. They can be broader or narrower and stronger or weaker. The strings apply their forces in different places and in various different directions along the bridge. So, with differently placed and directed taps we might identify a variety of formants, some closely related and others not.

The bridge formants of interest are those that are relatively strong and relatively wide in frequency. In particular they are strong and wide enough to enhance an identifiable frequency range.

FIG. 3. safer-at-home set-up

IV. MORE DETAILS

The actual set-up is shown in FIG. 3. A small microphone was clamped an inch or two from the head, right above the first string at the bridge. The computer recording volume was set as low as possible to emphasize the sound produced by the head directly beneath it over any more distant sources. A reproducible tiny force was applied to the bridge by wrapping a length of fine magnet wire around one string and pulling until it broke, while damping all the strings. The wire was looped around the string right at the bridge. Three pull geometries were employed: 1) up at the first string, 2) sideways at the first string, and 3) up at the third string. Those correspond to the hammer geometries used in ref.[1]. This approach was suggested by my collaborator, Jim Woodhouse, as a poor-man's alternative to his professional hammer/vibrometer set-up. To be sure, yet other geometries might capture other differences in the bridges' admittance formants, but these highlighted the strong enhancements observed in ref.[1].

I used 45 gauge magnet wire, D = 0.00176″. That's at the *very, very* fine end of the range for human hair. It's nearly invisible and breaks when you look at it.

An experienced acoustician might discern what's going on right away from the sounds themselves. I can't. But here is a sample of wire-break sounds for each bridge. In particular, it is the Smile, spillway, and Weitzel bridges (in that order), all pulled up at the first string, then all sideways at the first string, and then all up at the third string: Click here or go to http://www.its.caltech.edu/~politzer/bridge-hills/smile-spill-weitz-1st-side-3rd.mp3 .

They do sound different. To get a clearer indication of how those sounds differ, I turned to spectrograms for the same three kinds of wire-breaks on the same three bridges. Those are FIG.s 4, 5, and 6 below.

The bridges differed somewhat in loudness for the same strength of wire-break. I tried to get the heights of the initial sound recording amplitudes about equal by slight variations of recording level and distance. The results are displayed below as spectrograms. In that context, I made further slight adjustments to get the overall intensities below 1.5 kHz about equal. To be sure, a player might be interested in the comparative loudness of different bridges. But the present focus is on timbre. That is represented by the *relative* strengths of the signal over the frequency range (as well as their patterns in time).

In all comparisons, the patterns are very similar below 1.2 kHz, and considerable similarity continues up to around 2 kHz.

So, the action of interest is above 2kHz where the signal is getting weaker and weaker. (Note that human hearing is sensitive there, and timbre perception can depend on subtle differences.) To enhance the visibility of differences in the spectrograms (in addition to making some standard, typical choices for display options), I choose what Audacity calls "High boost, " i.e., 15 dB/dec. That's a high frequency filter or transfer function that is perfectly linear on a log-log plot with an increase of 15 dB in amplitude per decade of frequency. It's important that it is a totally smooth, linear function. It does not select or highlight any particular region. But the choice of 15 is arbitrary. I thought it did the job of emphasizing differences that ref.[1] identified using much more sophisticated techniques.

Your job is to see whether there are, indeed, regions of strong response that occur in different frequency regions for different bridges. The colors and their intensities represent amplitude or strength. White is the highest. Then comes dark blue, dark green, and then light green.

Ref.[1] identified two formants produced by flexing of a Smile bridge on an Eagle II. They were centered at 3.5 kHz and 5 kHz. The left columns of FIG.s 4 and 6 show particularly clear manifestations in this set-up of those phenomena. The other two bridges in the figures have different patterns of strong response.

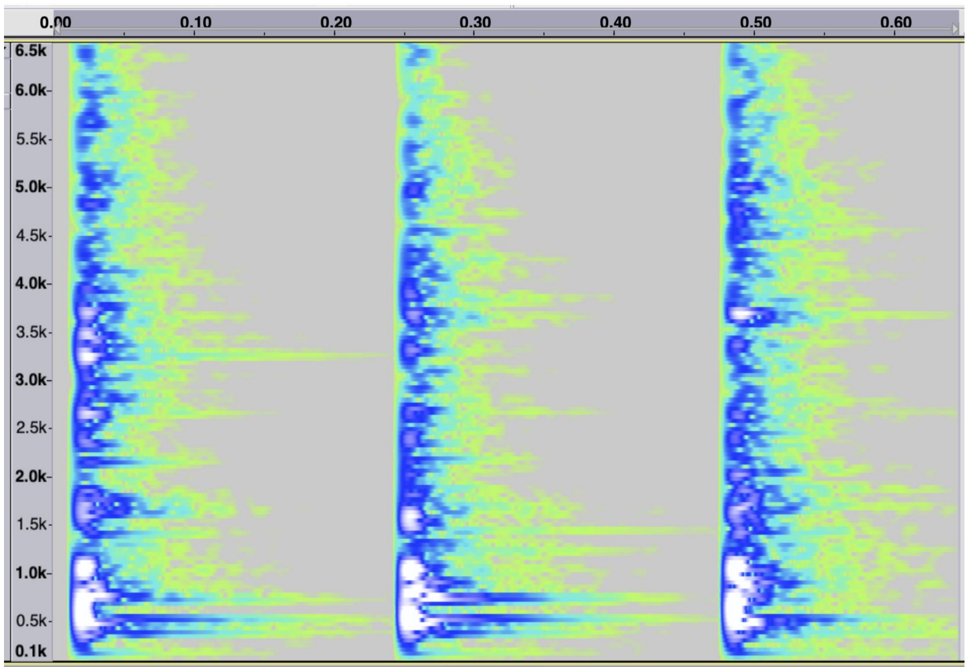

FIG. 4. (Left to right) Smile, spillway, and Weitzel bridge spectrograms — wire break, up at 1st string

V. SPILLWAY *VS.* WEITZEL 6-10 PLAYED SAMPLES

To hear an example of how differences in admittance (as approximated by the recorded wire-breaks) translate into the sound of actual playing, listen to these samples of the Deering Sierra with the spillway bridge and the Weitzel 6-10.

Click here for the spillway or go to

http://www.its.caltech.edu/~politzer/bridge-hills/spillway-JH.mp3 and

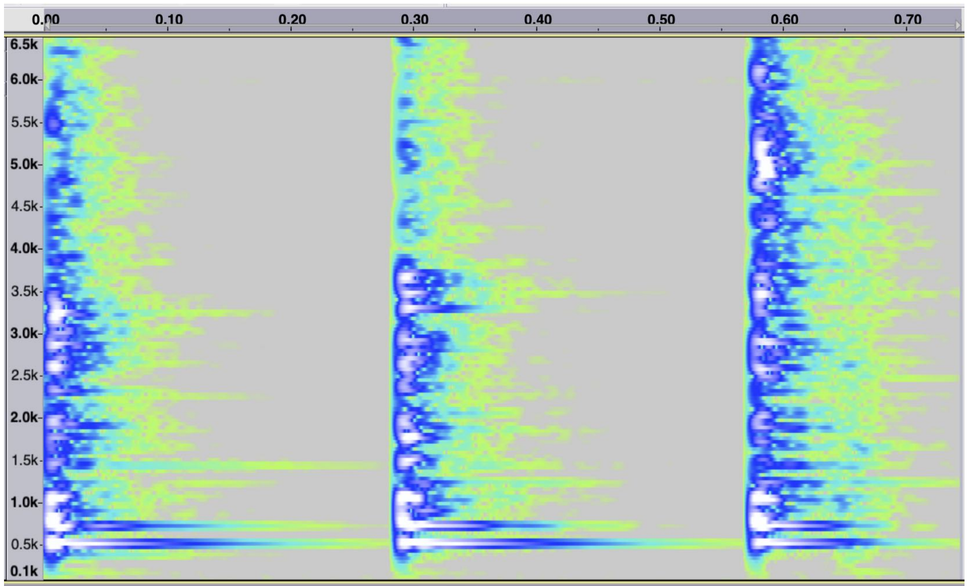

FIG. 5. (Left to right) Smile, spillway, and Weitzel bridge spectrograms — wire break, sideways at 1st string

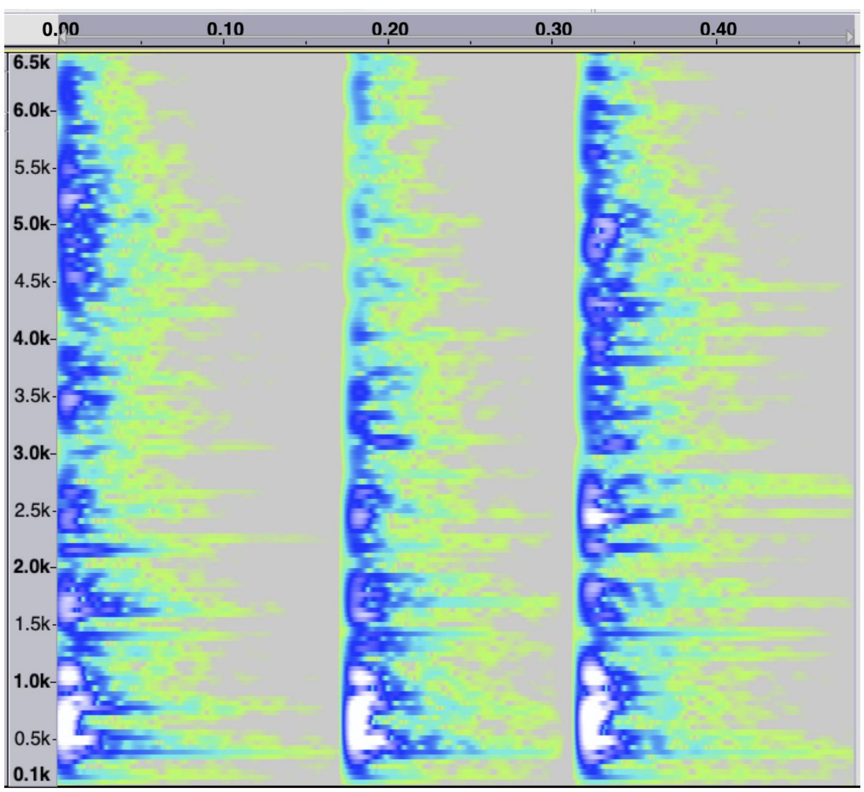

FIG. 6. (Left to right) Smile, spillway, and Weitzel bridge spectrograms — wire break, up at 3rd string

click here for the Weitzel 6-10 or go to
http://www.its.caltech.edu/~politzer/bridge-hills/weitzel-JH.mp3.

Referring back to the spectrograms, these are "columns" two and three in FIG.s 4, 5, and 6. There are small differences in the wire-break pulling up on string 1 (FIG. 4) and very big differences in pulling sideways on 1 (FIG. 5) and up on 3 (FIG. 6). Played string vibrations act on the bridge in both directions. So all three wire breaks are relevant to the played sound.

VI. SMILE VS. GOODTIME COMPARISONS

The photo on page 1 shows obvious grain differences of the maple between the two Deering bridges (i.e., the Smile and the Goodtime). This test reveals how they differ in turning string motion into motion of the head and into sound. The spectrograms are FIG.s 7, 8, and 9.

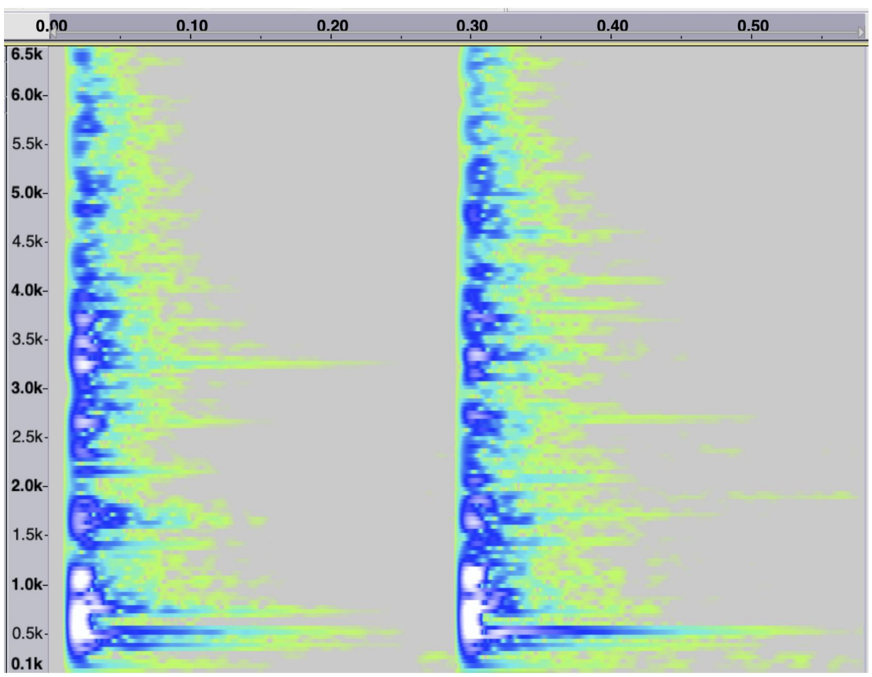

FIG. 7. Smile (left) and Goodtime (right) bridges — wire break, up at 1st string

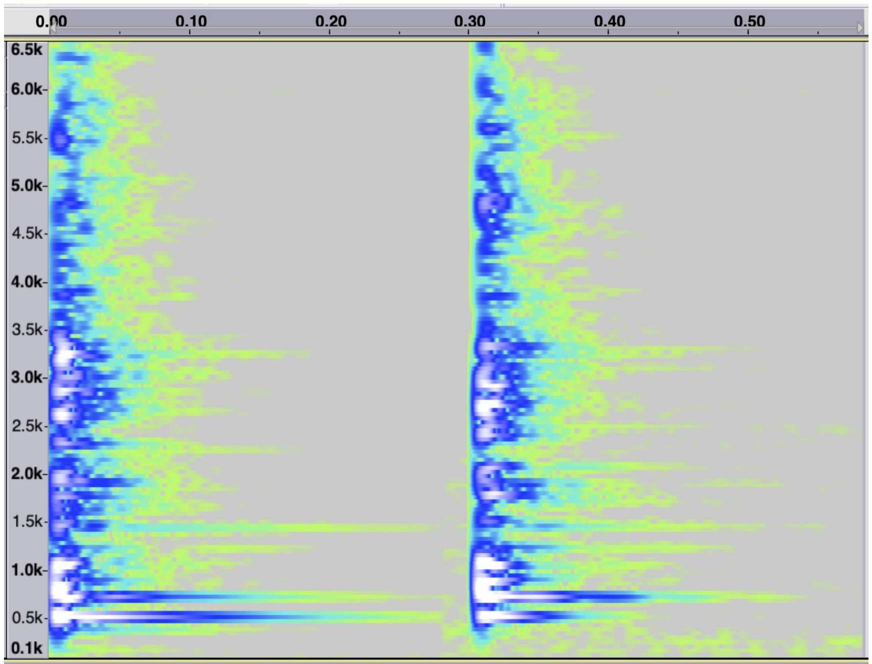

FIG. 8. Smile (left) and Goodtime (right) bridges — wire break, sideways at 1st string

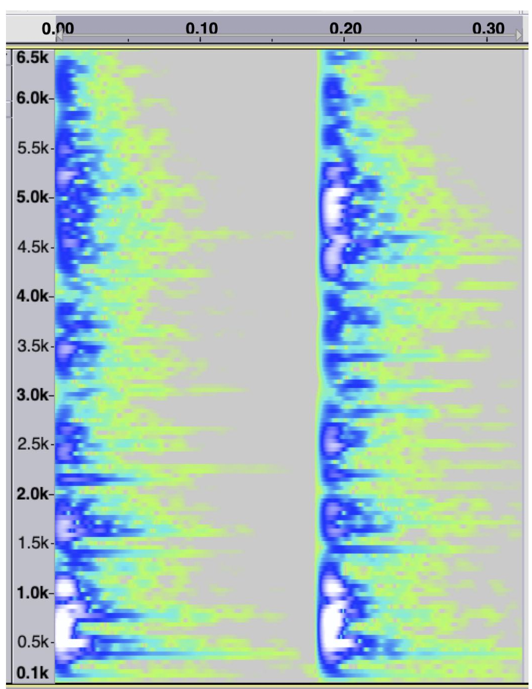

FIG. 9. Smile (left) and Goodtime (right) bridges — wire break, up at 3rd string

VII. SPILLWAY VS. WEITZEL VIOLIN

The Weitzel violin bridge is compared in the same fashion to the spillway in FIG.s 10, 11, and 12.

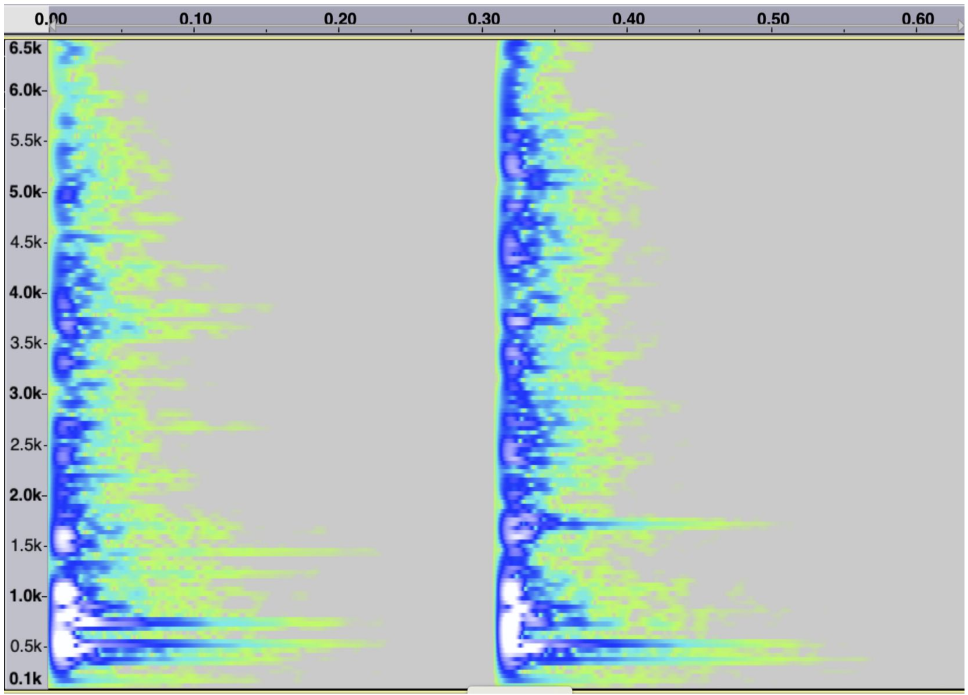

FIG. 10. spillway and Weitzel violin bridge — wire break, up at 1st string

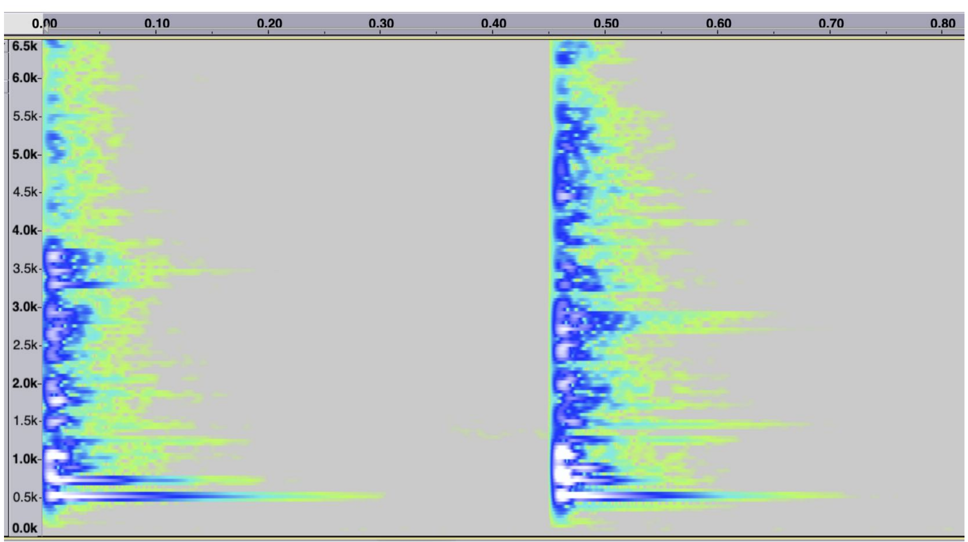

FIG. 11. spillway and Weitzel violin bridge — wire break, sideways at 1st string

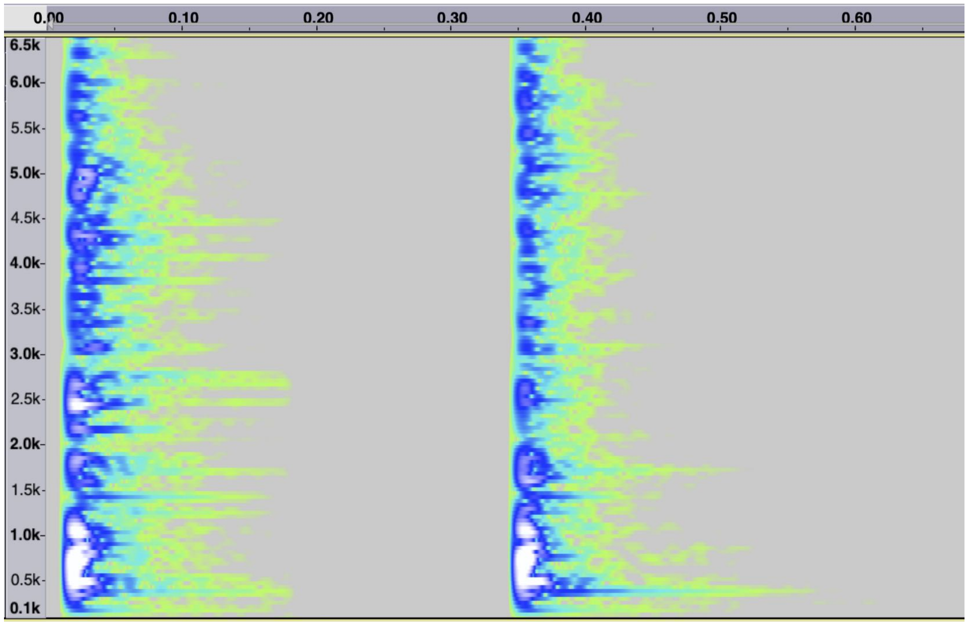

FIG. 12. spillway and Weitzel violin bridge — wire break, up at 3rd string

VIII. THE SAME BRIDGE ON DIFFERENT BANJOS

Ref.[1] identified the high frequency formants with dramatic bridge flexing. However, the associated formant central frequency need not match a resonant frequency of the bridge on its own. That's because any motion of the bridge feet has to match the motion of the head directly below. The two systems are strongly coupled. The formant represents a resonance of the combined system. Hence, the same bridge can emphasize different frequency regions on different banjos.

The bridge comes with its own mass, height, and flex characteristics. The most relevant aspects of the rest of the banjo, according to ref.[1], are string and head materials (masses and Young's moduli) and break angles. So, the Weitzel violin bridge was tested on a Colin Vance iOTA (shown in FIG. 13) to compare it to its performance on the Deering Sierra. The resulting spectrograms are shown in FIG. 14. The Sierra head tension was much higher than on the iOTA, and the break angle was sharper. Both of these are expected to raise the frequency of the main low formant, i.e., the strong response below 1.3 kHz. That is clearly apparent in FIG. 14. In that regime, the bridge contributes inertia but no particular return force to the oscillatory motions. However, there is no simple pattern to the higher frequency responses, where bridge flexing is, indeed, part of the return force, and the relevant inertia is not simply the total bridge mass. The point here is that even the sound features that can be attributed to the bridge particulars are different in the two situations.

Raising the frequency of the lowest formant by increasing head tension and break angle is an example of what formants do to the sound. Plucked strings apply particular forces to the bridge. Admittance determines how much the bridge moves (and produces sound). And a formant is a particularly strong frequency region of admittance. The wire-breaks produce a particular, *very* broad range of driving frequencies. The lowest intense region FIG. 14 shows how the produced sound responds to increased head tension and break angle.

FIG. 13. Colin Vance iOTA set up

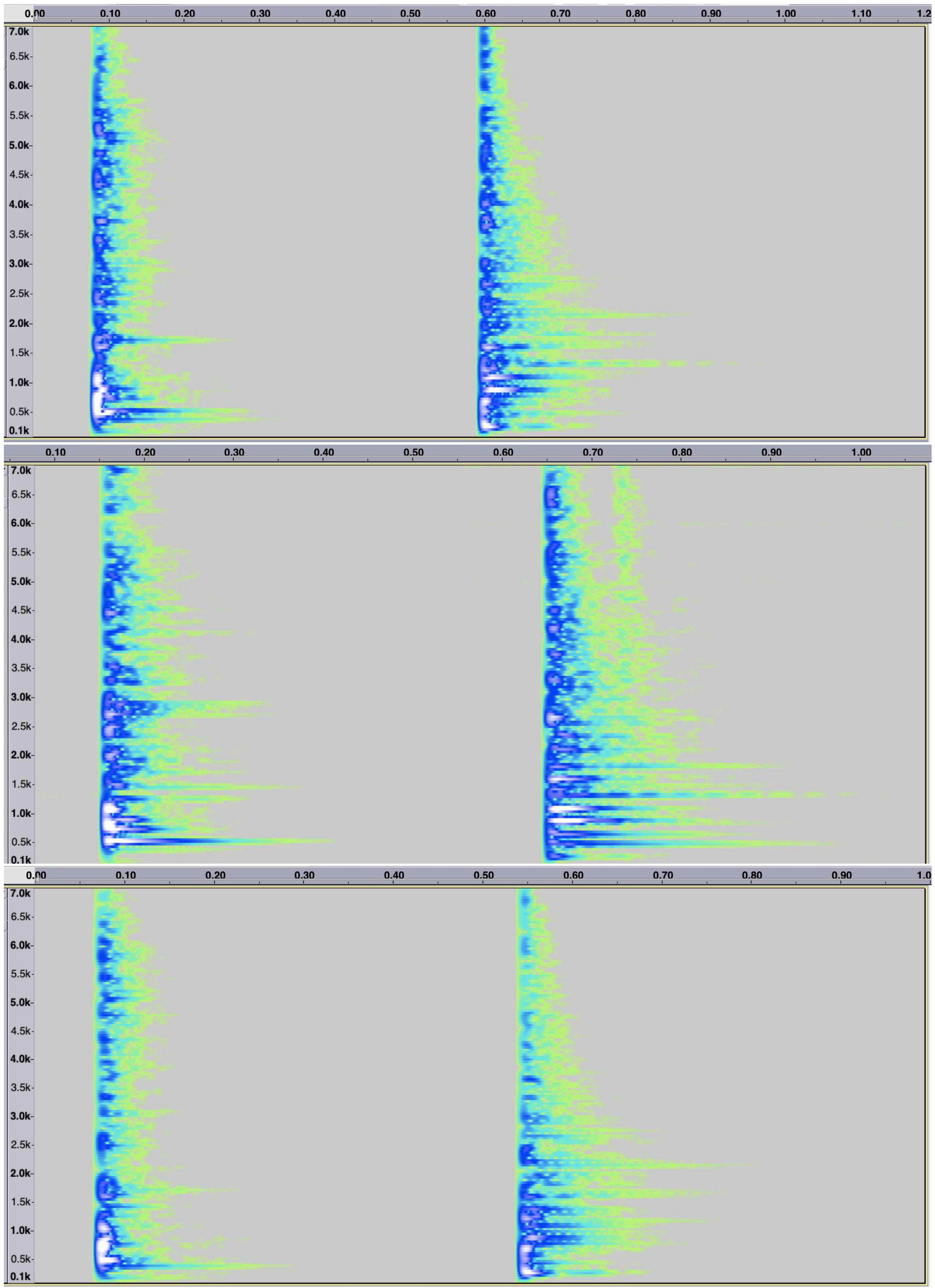

FIG. 14. Sierra (left) and iOTA (right) with the same violin bridge — wire break, up at 1st, sideways at 1st, and up at 3rd string

IX. VIOLIN BRIDGE MODIFICATIONS

On his Web site, Jeff Weitzel writes, "My own initial violin style bridge design had only two feet and was really just a violin bridge squished down to 5/8″. But physics dictated that a 3rd foot be added to avoid breakage and warpage." The middle foot is visible as a

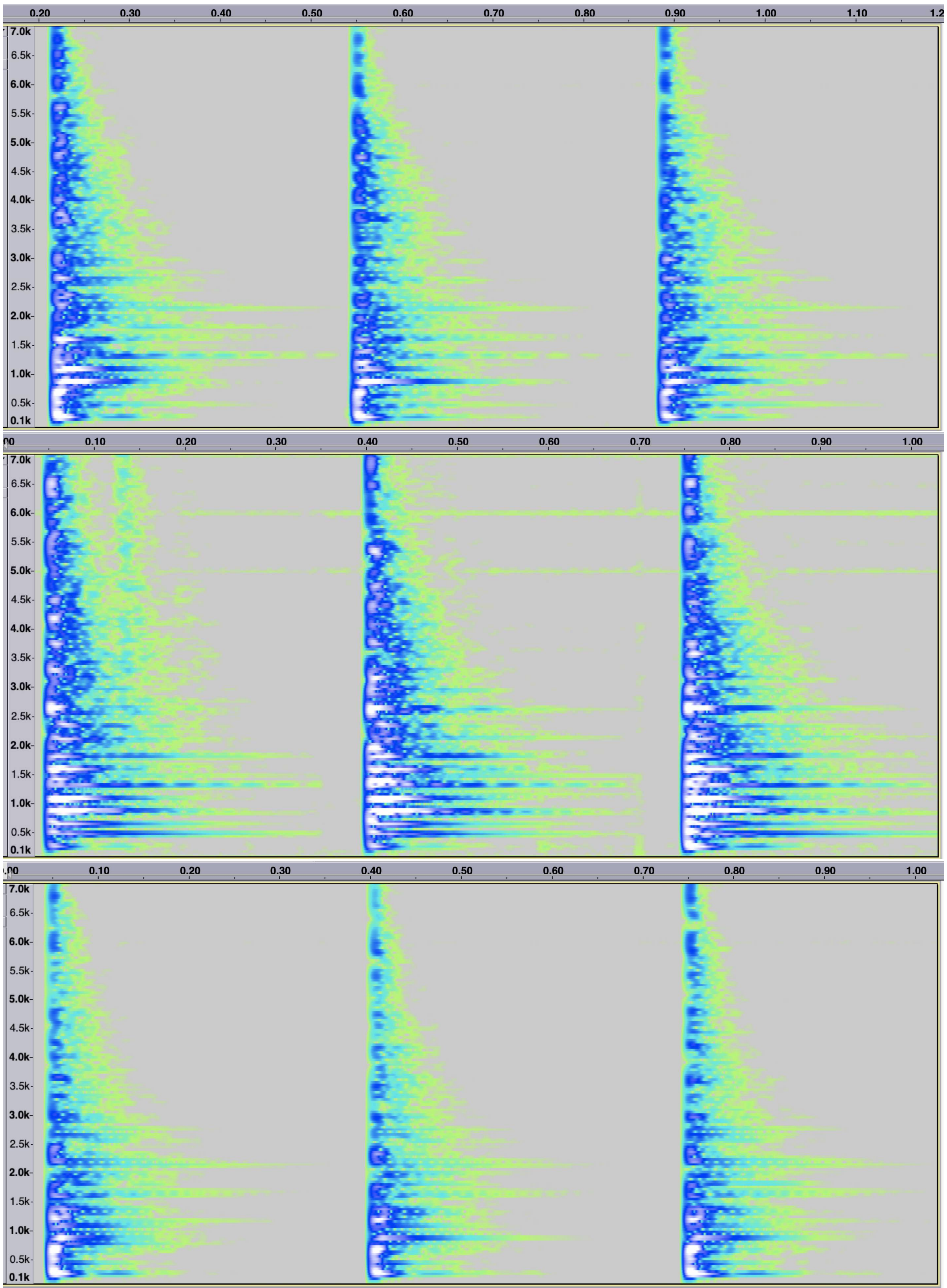

FIG. 15. three original violin bridges (across); wire breaks up at 1st, sideways at 1st, and up at 3rd

small tab in the photo on page 1. I thought that two tiny bits of surgery might alter the performance of those bridges substantially. So I ordered two more.

A. Modifying the Weitzel violin bridge

The three violin bridges looked identical when delivered. Spectrograms of the three canonical wire breaks are shown in successive graphs in FIG. 15. The three bridge weights are, left to right, 2.3, 2.5, and 2.4 gm, with the heaviest in the middle. The microphone distances and recording volume settings were the same for all three. (The sideways breaks are inherently much quieter; so the recording amplitude was set higher by the same factor for all three.) The performance of the different bridges is clearly quite similar. The small mass differences have no apparent, systematic effect. The differences that do appear are likely due to wood, fabrication, and break technique/set-up variations. This comparison gives a sense of the variation to be expected between different individuals of the same design.

The bridge surgery is pictured in FIG. 16. The first bridge is the original. The middle foot of the other two is shaved sufficiently that it does not contact the head when played. In addition, on the second bridge a slit is cut from the bottom up to the hole in the center. The wood removal reduced the weights by only 1 and 2% losses respectively. The resulting spectrograms are in FIG. 17, with the bridges in the same order, left to right, as in the photo, top to bottom.

FIG. 16. the original and two altered Weitzel violin bridges

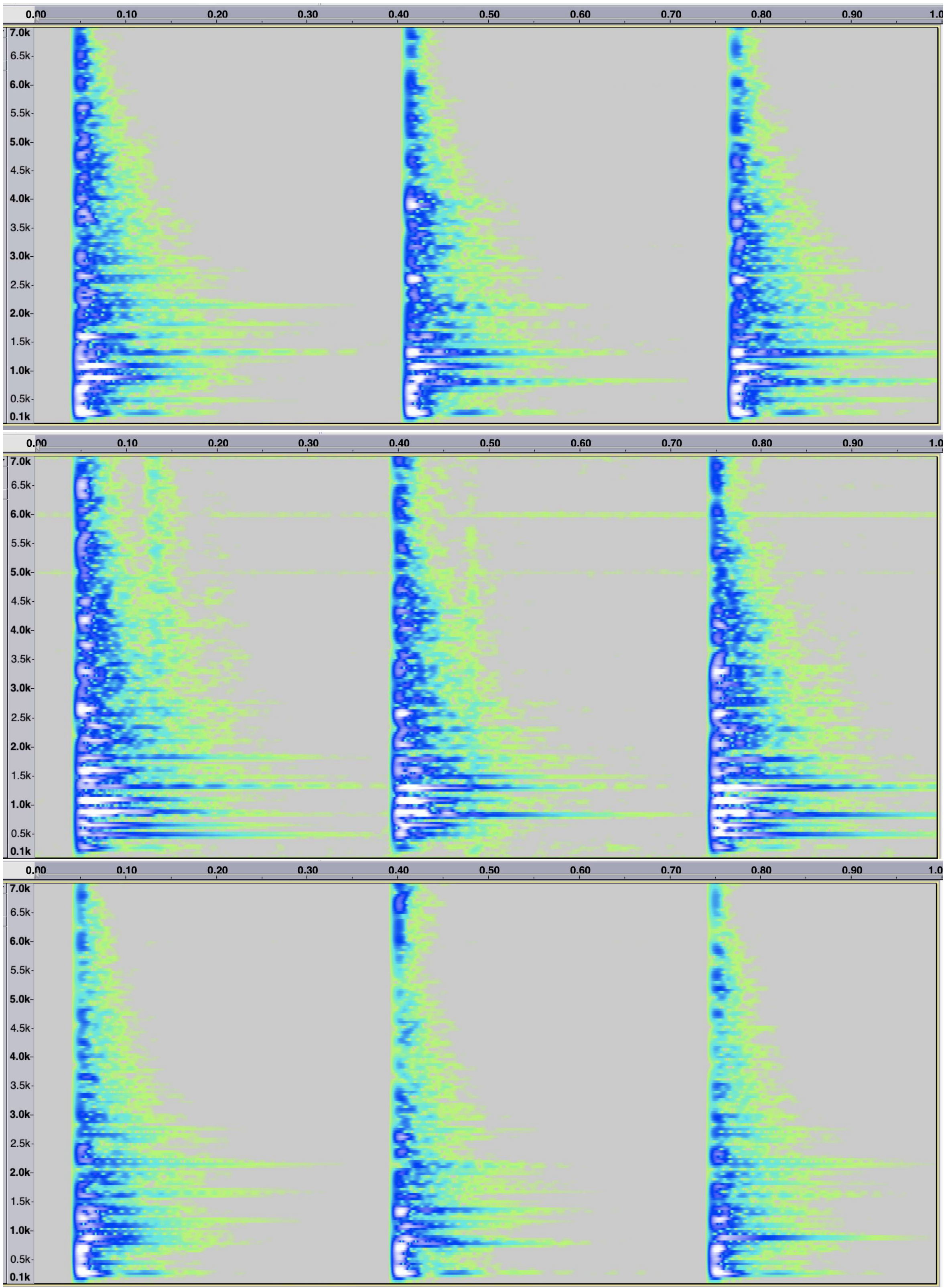

FIG. 17. violin bridges – across: original, shaved&split, shaved); down: wire breaks up at 1st, sideways at 1st, and up at 3rd

X. WHY ARE BRIDGES BRIDGE SHAPED?

The seven bridges studied thus far are all designs that players actually use. The lesson of ref.[1] is that, with all having essentially the same heights and weights, the relevant differences are their flexing motions under differently applied forces. That suggested that a solid block might provide the greatest contrast. Safer-at-home left me with a bit of poplar which I fashioned into a block of the same height and weight as all the other bridges. (See FIG. 18.) For direct comparison, I went back to the Deering Smile. Doing it on the Vance iOTA provided a second example of same bridge on different banjos.

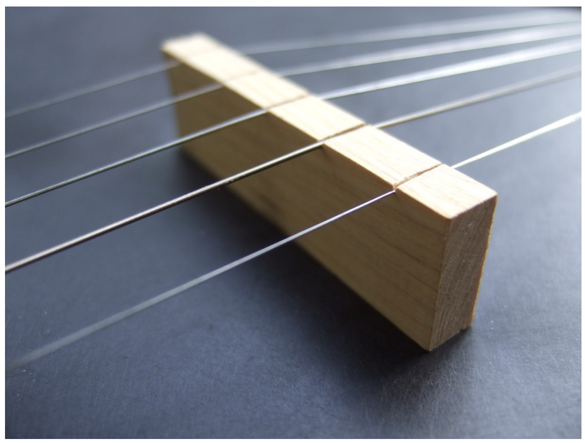

FIG. 18. poplar block bridge

FIG. 19 shows the performance of the Smile bridge on the Sierra *versus* the iOTA. As observed in **§VIII**, the higher head tension and break angle on the Sierra raises the frequency of the strong low frequency response. But the higher frequency response is simply... ...different.

And, finally, FIG. 20 displays the comparison of the Smile bridge and the poplar block on the Vance iOTA.

The block is distinctly less lively above 2.5 kHz. Presumably, the bridge shape of bridges allows the observed variety of different high frequency enhancements, depending on the details of the design. Indeed, many of the design modifications of banjos in the past two hundred years have pushed for more sound at high frequencies. However, there have always been some people who prefer the older sounds. Many 19$^{\text{th}}$ Century designs are still made today, albeit in small numbers. And many people strategically stuff the inside of modern banjos, not to make them quieter overall but specifically to suppress the high frequency

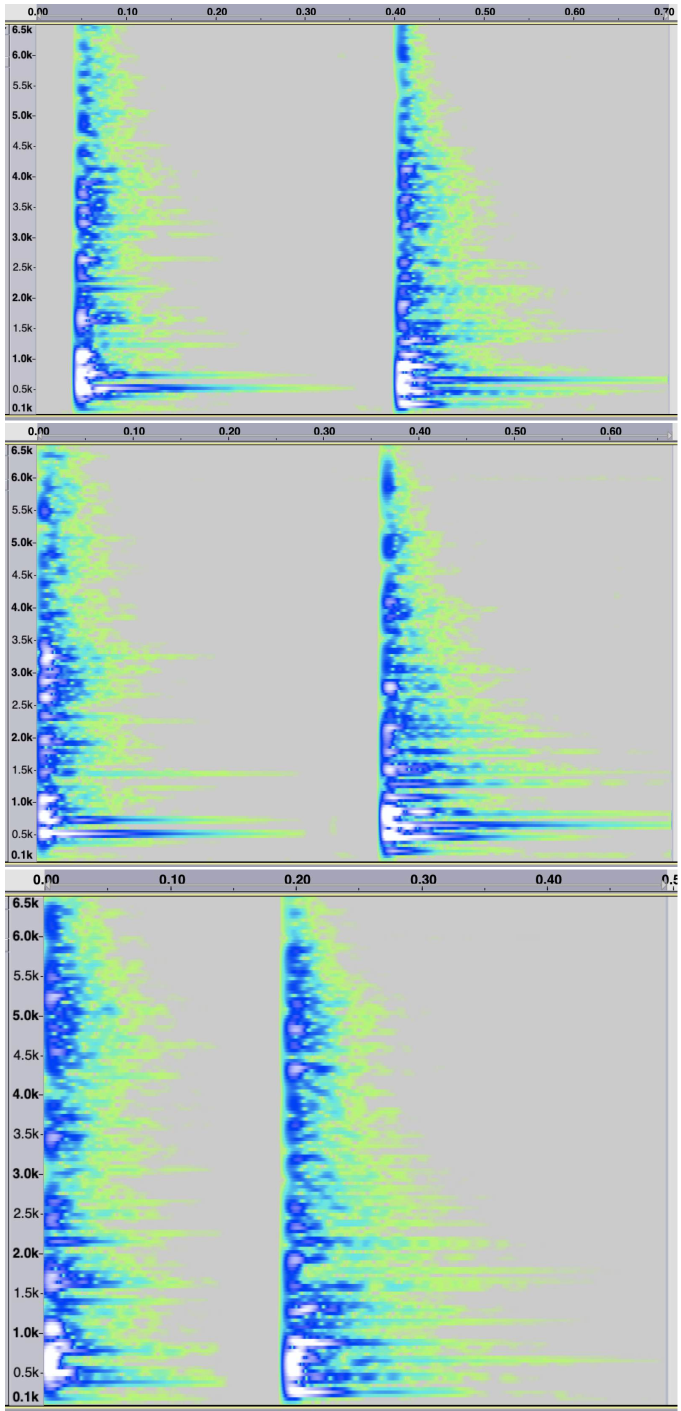

FIG. 19. Smile bridge on the Sierra (left) and iOTA (right): 1st up, 1st sideways, 3rd up

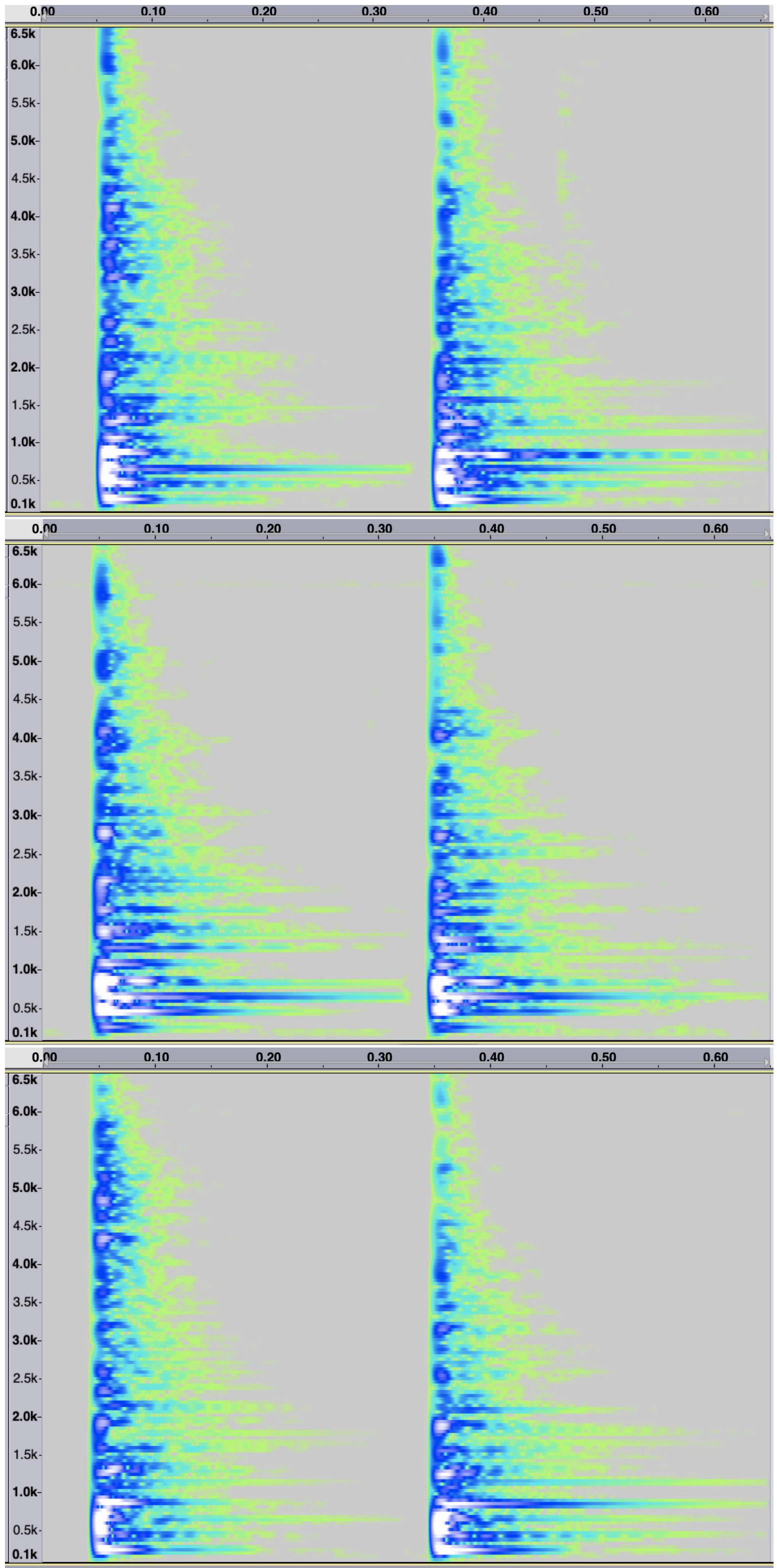

FIG. 20. smile *vs.* block on the iOTA: 1st up, 1st sideways, 3rd up

elements of their sound. Maybe they'd like a simple block bridge. Here are short sound samples:

Click here for the Deering Smile or go to
http://www.its.caltech.edu/~politzer/bridge-hills/smile-JH-iota.mp3 and

click here for the block bridge or go to
http://www.its.caltech.edu/~politzer/bridge-hills/block-JH-iota.mp3.

(The actual sound on these two is pretty crappy and does not do the iOTA justice. The head tension was set to emphasize contrasts with the Sierra. However, it was significantly lower than appropriate for normal playing. Also, it is designed for a higher bridge than the 5/8″ bridges in this study, which were chosen to match the one used in ref.[1]. The net result was **very** *low action. These choices were made for the wire-break comparisons. But the iOTA set-up gave a disappointing sound. Nevertheless, the comparison is relevant.)*

In a similar vein, a thin piece of wood (e.g., $1/16'' \times 5/8'' \times$ {the length of the bridge footprint + 1/2″} is well-known to tame high harmonics. A bit of tongue depressor works well. The effect is to dramatically reduce the large motions in different directions under the bridge feet that are responsible for the high frequency formants.

XI. WHY WOOD SPECIES MATTERS

Wood is highly anisotropic, which impacts its stiffness to flexing. So, grain matters. Stiffness is strongly correlated with density. Hence, in a crude sense, pieces of different species but the same weight can be comparably stiff. However, the relevant flexing can be three-dimensional. And bridges of different density with the same total weight cannot be the same shape as three dimensional objects. One's immediate impression of a bridge's shape is its two-dimensional profile — as in the photo on page 1. However, there is always a thickness and a thickness profile. Imagine bridges made of two different species with very different densities. With the same weight and 2D profile, the denser wood bridge will be thinner in the third direction. The two bridges may be comparably stiff to bending in the 2D plane. But the denser bridge may be more flexible in the third dimension.

XII. RECAP OF LONGITUDINAL SOUND IN BRIDGES

Sound in air is a wave of pressure variations produced by *longitudinal* vibrations of the air. "Longitudinal" means that the compression and rarefaction of the air is along the direction of the wave motion — as opposed to the plucked string vibrations, whose musical manifestations are overwhelmingly transverse to the string.[2] Wood also supports longitudinal compression waves. The longitudinal wave speed in hardwoods is 10 to 12 times faster than sound in air. For acoustic frequencies, the wavelengths are at least 20 times greater than the height of a typical bridge. That means that, when longitudinal sound travels *through* the wood, the bridge moves as a rigid, single unit, with no meaning to that sound taking different possible paths. In contrast, bridges can flex at acoustic frequencies in a great variety of ways under the influence of the forces from the strings.

The solid block "bridge" optimizes solid wood along what some people imagine is the "direct path" of sound from string to bridge. However, all the other bridges tested here give livelier performance at high frequency.

XIII. CONCLUSION

To repeat, bridges can flex in a great variety of ways under the influence of the forces from the strings. The impact on banjo sound is not something one can intuit or deduce from simple considerations because the geometry of the bridge feet and the vibrational modes of the head all work together with the flexing of the bridge. In ref. [1], sophisticated finite element numerical modeling of a three-legged bridge and head identified the bridge motions that produced enhanced frequency ranges in the response to string vibration. So, there is no breakdown of the rule of simple physics. In fact, linear physics does a reasonable job of accounting for bridge performance. It is working out the actual solution of those differential equations for complicated geometries that is not at all simple.

The term for enhanced regions is "formant." Ref. [1] found bridge formants around 3.5 kHz and 5 kHz. The measurements here for the same type of bridge on a similar banjo reproduce those enhanced regions, as shown in the left hand "column" of FIG.s 4, 5, and 6 — with the 3.5 kHz clearest in FIG. 4 and 5 kHz in FIG. 6. This investigation shows how that plays out differently for other bridge geometries and when placed on different banjos.

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[1] *Pickers' Guide to* Acoustics of the Banjo, D. Politzer, J. Woodhouse, and H. Mansour, HDP: 20 – 01, http://www.its.caltech.edu/~politzer – APRIL 2021; a longer, more technical exposition is available as open-access as *Acoustics of the Banjo: measurements and sound synthesis & theoretical and numerical modelling*, 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).

[2] For an example of longitudinal string vibration music, do a Web search for Earth Harp and William Close. Ellen Furman first assembled her Long String Instrument some twenty years before the first Earth Harp, but she has a very different idea of music.