Banjo Bridge Wood Comparisons

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Sound measurements with just a few banjo bridges of matching weights and designs but different wood species, using rather simple apparatus and protocols, support two widely held notions: 1) Different wood *does* sound different but 2) not *very* different. In this respect, bamboo and mahogany did not perform radically differently, nor did walnut *versus* spruce. The observed small differences were sufficiently complicated as functions of frequency that no account in terms of simple physics seems likely.

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I. PROLOGUE

The opportunity to meet face-to-face was too good to pass up. In addition to sharing stories and perspectives, we decided to focus on something specific in "banjo physics," as much to learn from each other as to advance the frontier of acoustic science. Given only a *very* limited time, we settled on wood varieties in bridges as something of general interest. This note reports what we tried and what we found with a rather modest effort.

II. THE SET-UP

Bridges transfer vibrations from the strings, where the music vibrations start, to the head, which puts those vibrations into the air. The weight of the bridge impacts loudness, sustain, and tone.[1] To focus on the role of wood species, we decided to compare bridges of the same weight. (For reference, APPENDIX A compares 2.2 and 3.5 gm bridges of the same wood and design. The most obvious impact of weight on playing is note "separation," the decay of a plucked note before the next one is sounded. This is quantified in APPENDIX A. Small spectral frequency shifts are also observed.)

The geometrical design of the bridge can also effect the sound. One issue is the relative importance of direct transmission through the wood (by waves of compression [i.e., sound]) *versus* flexing of the overall shape, which is sensitive to some parts being thinner and some thicker. Another issue is the footprint. One can move the feet apart or sideways or contact a larger, smaller, or just different area of the head. With these in mind and a goal specifically to investigate wood varieties, we chose to compare different woods using the same bridge design. To obtain the same weight, the difference in the varieties' densities was compensated largely by the thickness, a change which has the smallest possible impact on flexing or footprint.

The basic idea is to apply a force of a given frequency to the top of the bridge, essentially doing what the strings do. One then observes what comes out the bottom of the bridge, i.e., how it drives the head. The ratio of the force (applied to the top) to the velocity of the bottom is technically known as *impedance* (or its inverse, which is *reactance*). This measurement is performed for the full range of relevant frequencies, using forces appropriate in

magnitude to the actual playing of the instrument. Professional acousticians use a high-tech array of linear motors and stress and strain gauges, all well-clamped in careful registration, to assure reproducible results. For the present investigation, a much lower-tech approach was used.

FIG. 1. Original set-up in the LeVan Studios

Well-controlled frequency sources are readily available from voltage generators. The force comes from a piezoelectric element which reliably expands and contracts in proportion to the applied voltage. The magnitude of the force which the piezo applied to the bridge is not

known, but it is more or less reproducible, which allows a relative comparison of different bridges. And, finally, the motion at the bottom of the bridge is monitored through the sound produced by the head. Again, the only thing changed from bridge to bridge is the bridge itself; banjo, head, piezo, and mic are left unchanged.

With all strings at normal tension, a piezoelectric disk, with a bit of felt on top, was tucked between the third string and the top of the bridge. All strings were damped. The piezo was driven sinusoidally by a signal generator at a constant voltage amplitude, with a slow, logarithmic sweep from 160 to 18,000 Hz, and the produced sound was recorded. Variation in positioning the piezo on the bridge — in spite of our best efforts to repeat it identically — introduced a possible source of difference between the two weight-matched bridges in a single pair.

To estimate the variation due to positioning and to reduce its impact on the analysis, we alternated sweeps, doing one bridge and then the other. That way, every sweep was subject to the same sort of possible positioning variation. Recordings were made in the LeVan Studios on a fine LeVan banjo. The set-up is shown in FIG. 1.

The differences between bridges were barely more than the differences from sweep to sweep on a given bridge. On return to the Politzer Lab, a couple of minor changes were implemented, with the aim of enhancing the bridge-dependent part of the signal — and that is the data presented below. The microphone was placed as close as possible to one of the bridge feet. That location should maximize the ratio of direct sound from the immediate vicinity of the foot of the bridge to sound from other parts of the banjo and sound reflected around the room. Also, to maximize the bridge-foot direct-sound relative to wave reflections in the head from the rim, a rubber tone ring was installed[2], and the head tension was relatively low (i.e., 84 on a DrumDial). Further damping of the secondary sound (i.e., sound not generated directly at the bridge foot) was attempted by including an extra layer of short-pile carpet along with the "synthetic belly" [3], all mounted flush to the rim, with no air gap or open-back "sound hole," at the open back, shown in FIG. 2.

This is a good time to emphasize that the quantitative comparisons we were seeking do not depend on the particular banjo used. We are not asking what sounds good or what sounds better. Rather, the issue is how do bridges differ in their effect the final sound. With all other aspects held the same (or as similar as possible) in a particular comparison, we look at the differences between the sounds. The bridge takes the string vibration as input

FIG. 2. Set-up used for the piezo scans reported here

and transfers it, with some modifications, to the head. Under the approximation that the whole system is "linear"[4], the role of the bridge is separately identifiable and distinct. A given bridge will have the same transfer characteristics in whatever situation it is used.

III. THE SOUNDS OF PIEZO-DRIVEN FREQUENCY SWEEPS

A. Bamboo *versus* Mahogany

The first pair consists of 2.5 gm bridges of bamboo and mahogany. FIG. 3 shows the recorded sound levels in dB as functions of frequency (in Hz) for six sweeps each. (Those are the thin lines.) The thick lines are the averages of the six for each wood type, and the thick line at the top is the ratio of the average sound signals (i.e., the difference in dB).

The sweeps show variation from one another, but there are trends and tendencies dis-

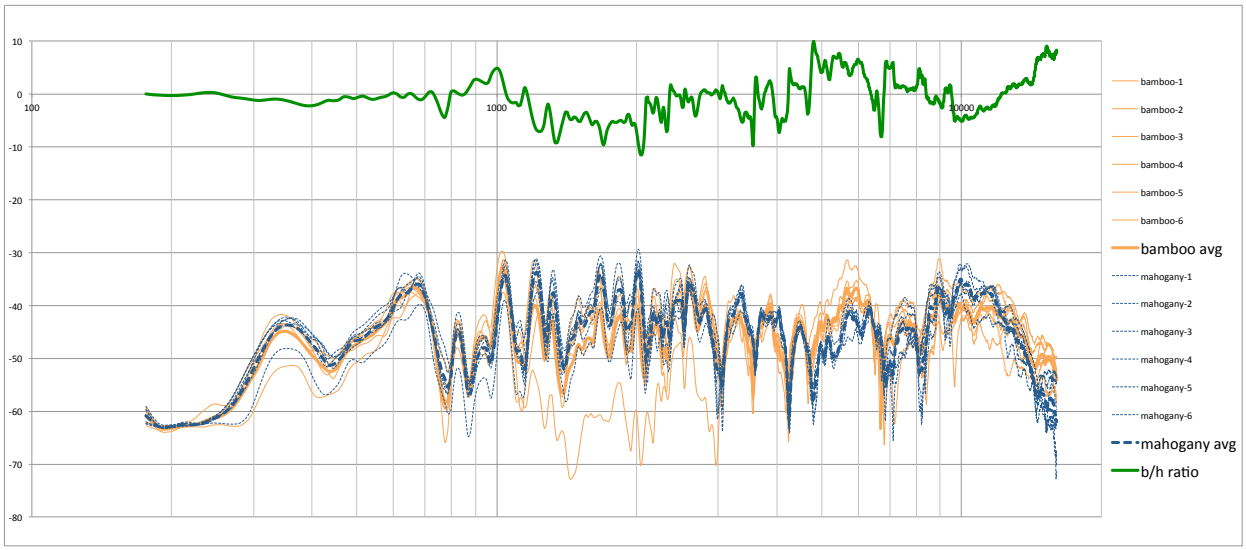

FIG. 3. Bamboo and mahogany runs, averaged and compared; sound in dB *vs.* frequency in Hz

cernible. These trends are represented by the averages and displayed in a clear way by their ratio. More runs might give a more convincing result — because the fractional statistical noise in the average of N runs typically decreases like $1/\sqrt{N}$. Alternatively, more attention could be made to improving the reproducibility of the registration of the piezo onto the bridges. We simply positioned the piezo flat on the bridge cap by eye. To attempt this sort of measurement in the future, perhaps a further piece of hardware could be designed and fabricated to align the piezo and string slot automatically so that it would sit and make contact the same way each time.

In the real-world situation of actually playing the banjo, there is certainly some variation from each installation of the bridge and from minor variations such as wear, dirt, or the cut of string notches in the top of the bridge.

From 180 Hz up to about 1200 Hz, the interval where the first few harmonics of played pitches reside, the two bridges are actually quite similar. At yet higher frequencies (which also play a role in banjo sound), there are frequency ranges where the differences reach to around 6 dB and occasionally hit 10 dB, which might be discernible in normal playing — if, indeed, those were important regions for the particular banjo and tune played. However, sometimes one wood is louder and sometimes the other, offering no suggestion of something simple underlying the behavior.

B. A Comment on Plots — a technical digression

There are several choices in making the recorded data intelligible in some graphic form. The choice made here is frequency spectral analysis. Decibels are a natural choice for units of strength or loudness. While they do not exactly match human perception of loudness, they are far closer to that perception than linear energy or power units. Any spectrum evaluation has an implicit resolution in frequency. For a system with many nearby and overlapping resonances, one may choose to resolve the individual details or average over them. There is no single, right choice. Rather, it depends on what one wants to understand or highlight. A given spectrum calculation (a "Fast Fourier Transform") will have a given resolution, and a particular choice may or may not be appropriate, depending on what information one wants to extract. Displaying frequency on a logarithmic scale matches human notions of pitch; each octave corresponds to a doubling of frequency. For the total audible range, a log plot emphasizes the region of fundamental pitches and their lowest harmonics. Higher frequencies, if presented with the same frequency resolution are something of a jumble — all squished together. In contrast, a display that is linear in frequency squishes lower harmonics all together. If there were a particular region of frequency that was clearly related to some particular physics, one could highlight that region appropriately. In the present investigations, no such region made itself manifest. Hence, rather than display the results in all possible ways (and overwhelm the reader), we chose to make a single compromise of resolution and scales for all sound recordings over the whole audible spectrum.

C. Spruce *versus* Walnut

A matched 2.1 gm spruce-walnut pair were also compared. The results are in FIG. 4. The scatter from run to run among the six for each bridge was similar to the bamboo-mahogany pair. Only the averages are displayed here. The difference between the two woods is mostly smaller than for bamboo and mahogany. The spruce and walnut are quite similar up to about 3500 Hz, and many of the higher frequency differences span only small intervals of frequency.

Even if the data presented here represents real properties of the particular bridges investigated, there are important caveats. Only one bridge of each wood species was tested. But

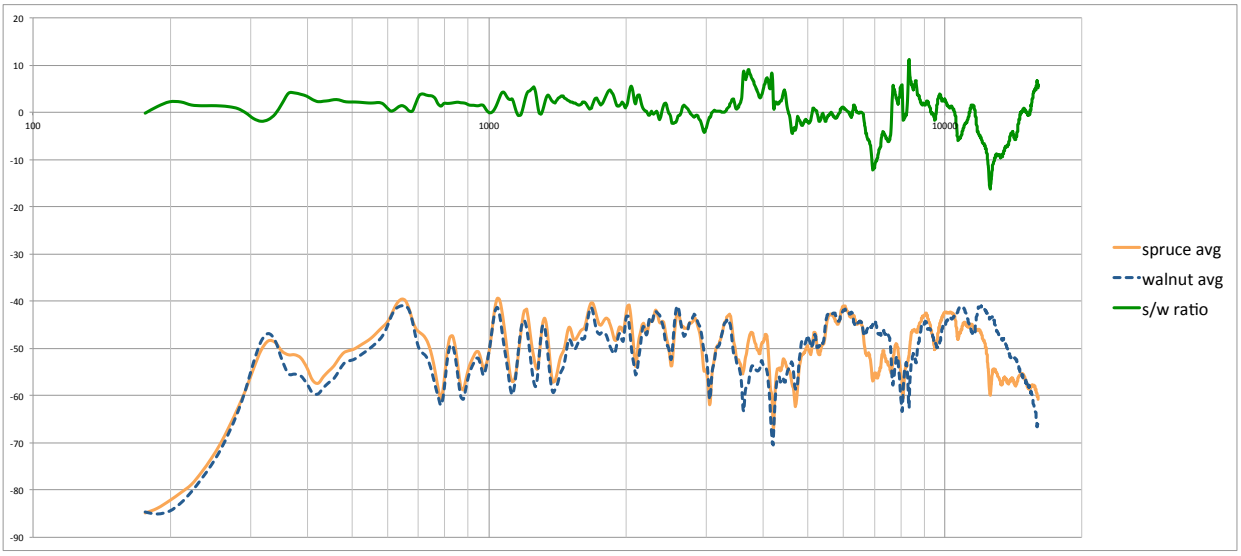

FIG. 4. Spruce and walnut runs, averaged and compared; sound in dB *vs.* frequency in Hz

bridges are small enough that grain variations can be expected (and are known) to cause differences in sound. Also, the single aspect of the bridge response that is reflected in these measurements may not play an important role in what people listen for in the sound of a banjo. Furthermore, there is a big difference between steady notes, which is what were recorded here one frequency at a time, and plucked notes. As plucked notes decay, their timbre changes. The frequency dependence of that decay doubtless leaves an impression on the listener. And bridges play an important role in that frequency dependence.[5]

These particular examples of bridges were chosen out of the LeVan collection to be weight-matched pairs with very different materials. The differences in the wood are largely matters of density and hardness. Indeed, bridges constructed to the same dimensions would have very different weights and very different flexibility. But matching the weights by adjusting the thickness may well make the softer, less dense bridge as stiff as the dense, hard one.

IV. REAL PICKING

How do those bridges sound? Here are recordings of a little bit of picking, in a single session, on the same LeVan banjo, with every effort made to change nothing besides the bridges themselves. To offer the possibility of a blind listening comparison, the bridges are labeled 1, 2, 3, and 4 (with an identification key given on the last page). (If your reading is

FIG. 5. The banjo used in FIG. 1 and for all sound files

Web-enabled, the following links might be live; otherwise they should be retrievable.)

http://www.its.caltech.edu/~politzer/bridge-wood/bridge-1.mp3

http://www.its.caltech.edu/~politzer/bridge-wood/bridge-2.mp3

http://www.its.caltech.edu/~politzer/bridge-wood/bridge-3.mp3

http://www.its.caltech.edu/~politzer/bridge-wood/bridge-4.mp3

FIG. 6 plots the computed spectra for the entire approximately 24 seconds of each LeVan bridge sound file in dB *versus* frequency (in Hz) from 180 to 16000 Hz on a log scale. The spectrum of each recording appears twice. First, each is displayed with its weight-matched partner. The lowest set of traces are the spectra of all four bridges. The off-sets are 25 and

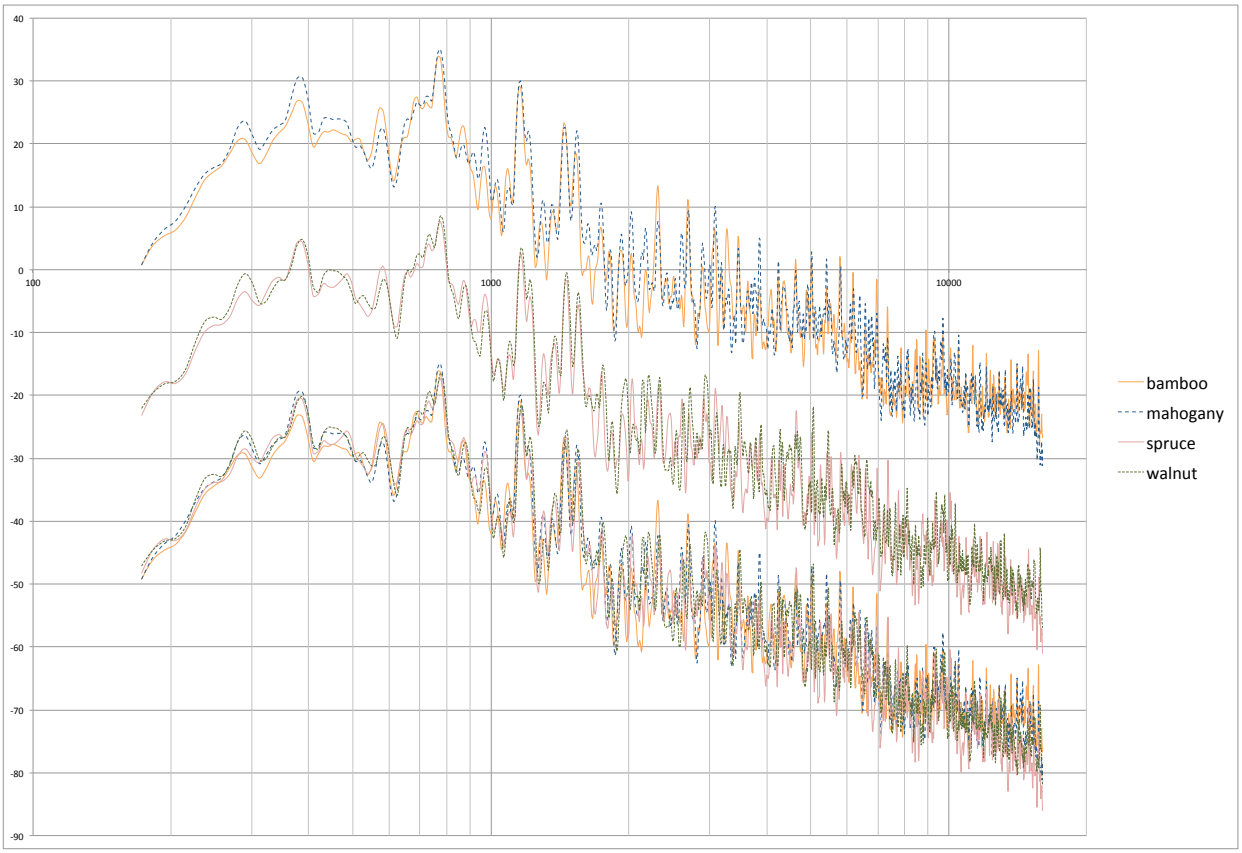

FIG. 6. LeVan bridge sound sample spectra in dB *vs.* from 180 to 16000 Hz (log scale)

50 dB, respectively.

V. CONCLUSION

It is certainly possible that the method used in these recordings gives a precision that masks their irrelevance. They simply might not be capturing the distinctions that people attend to when they listen.

It is also possible that the quantified differences are slight but nevertheless could help a particular banjo, with its own frequency strengths and weaknesses, reach a particular goal in terms of sound quality. It is commonly expressed that there is no "best bridge" (or banjo, for that matter). Careful listeners will make choices depending on the banjo on which is it installed and the desired sound.

And, finally, there is an alternative, rather different possible interpretation of these rather undramatic observations. It is a perspective occasionally voiced by professional builders but

not widely appreciated by their customers. Different wood species offer aesthetic value and often present different challenges in working with them. But the performance of the final product may be far less sensitive to the wood choice than often believed. Design and fabrication precision are certainly crucial. But variations in wood density and stiffness due to species and particular grain can be largely irrelevant in some contexts and something that can be compensated in others. "Irrelevant" could be because the piece works intimately with many other tightly joined pieces. And "compensated" could be by adjusting thickness and other shape aspects to get the desired performance. For example, Bob Taylor famously [6] built a guitar out of scraps from crates and pallets — just to demonstrate the point. Similarly, violin lutherie at the highest level certainly involves very careful selection of woods and very careful fabrication to predetermined outer dimensions. But a huge amount of further work is done on the inside of the instrument to get the particular, unique pieces of wood to perform as desired.[7]

There are two physics considerations that support this perspective for the particular case of banjo bridges. These regard sound propagation and flexibility. The speed of sound in wood is roughly ten times the value in air. It varies from species to species but in any case is so large that the traversal time for $1/2''$ to $3/4''$ of wood is tiny on scales set by acoustic frequencies. The wavelengths of sound in wood are consequently about ten times longer than they are in air for a given frequency. So, an object that is tiny compared to those wavelengths cannot be expected to effect sound propagation. ("Sound propagation" here specifically means waves of compression.) A bridge's shape can effect its acoustic performance through the effects of flexing. A given shape can act as a spring that has its own natural, resonant frequencies. (See APPENDIX B for further discussion.) These frequencies depend on the stiffness and mass of the wood, as well as the shape. In our comparisons of very different woods but with the same bridge design, the decision to match the weights matched to a significant extent the mass distribution and stiffness.

One might conclude that this was not a great way to compare bridges. Certainly, nothing beats listening. The goal here was specifically to explore the impact of wood species as a variable, holding other factors fixed. On the other hand, there are factors that effect what we hear besides the rapid pressure variations in the air. In the case of spoken sounds, there is the McGurk effect[8] wherein virtually all people hear what they see rather than the sound in the air. And double-blind tests with world-class musicians can't pick Stradivarius violins

from modern instruments that cost a fraction of 1% of the highest prices paid for Strads.[9] So, how different might banjo music be?

APPENDIX A: INCREASED WEIGHT

Two LeVan bridges made of maple offered an illustration of the effects of different weights, other things being (almost) the same. The weights were 2.2 and 3.5 gm. Here are small sound samples of actual playing, again on the same LeVan banjo, with every attempt to reproduce the performance:

http://www.its.caltech.edu/~politzer/bridge-wood/bridge-5.mp3

http://www.its.caltech.edu/~politzer/bridge-wood/bridge-6.mp3

The most obvious effect on normal playing of going from 2.2 gm to 3.5 gm is a decline of note separation. Rapidly played notes run into each other a bit. To investigate this particular aspect, first string plucks were recorded with the other strings damped, using the same banjo, back, and mic placement used for the frequency scans. With some practice, it is easy to produce a series of plucks that sound the same and even look very much the same plotted as recorded mic voltages *versus* time. (The following numbers refer to twenty plucks on each bridge.) Defining "rise time" as the time from the onset of the sound to the time of the highest peak in the recording, the 2.2 gm average rise time was about 0.005 seconds, corresponding to two or four oscillations of the strongest harmonic. The corresponding time for the 3.5 gm bridge was 0.009 seconds or six oscillations.

The decay of a plucked string, even with all other strings damped, takes complex forms and is certainly not a single exponential. (That's a consequence of the system having many coupled parts.[5]) A simple, relevant measure of the decay rate can be defined by the time it takes for the sound to decrease to 6 dB below its peak value. That's a noticeable diminution, and the corresponding time is a substantial portion of the period between rapidly played notes. Using the onset of sound as the initial time, that 6db decay time was 0.032 $\pm$0.003 seconds for the 2.2 gm bridge and 0.043 $\pm$0.001 for the 3.5 gm bridge.

The averages of the spectra for six piezo-driven scans of each of the two maple bridges are shown in FIG. 7. There is a slight hint of something going on beyond what happened with the weight-matched pairs. In the present case, there is just a bit more of changes in shape and location of the features of the spectra — and not just their amplitudes. 1.3 gm

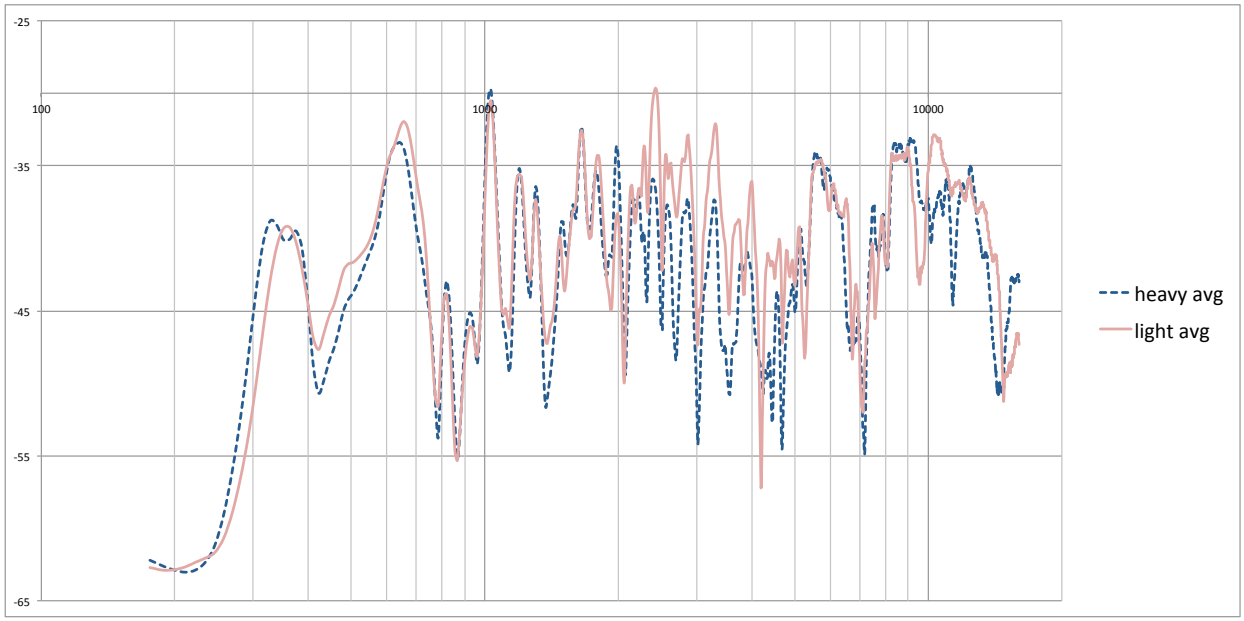

FIG. 7. Scans of the heavy and light maple bridges plotted *versus* frequency for 180 to 16000 Hz

is a large weight difference relative to the bridges themselves. But it is a small difference relative to the mass of the object that has to move to make the sound. That total mass includes the head and the immediately adjacent air (referred to in the discussion of drums as "air load.") A small change in mass of the oscillating objects will produce small shifts in the resonant frequencies.

APPENDIX B: Compression *vs.* Flexion

Consider a piece of steel. A cylinder will do. Tap it at one end. How long will it take before the other end moves? Equivalently, how long will it take for the compression caused by the tap to travel to the other end? That travel time is simply the length of the travel divided by the speed of the compressive pulse, which is the speed of sound. In steel, that speed is about 20,000 ft/sec. Varying the cylinder diameter along the way or even drilling holes in it will not alter that time appreciably. (Sound does not travel like bullets!) There might be some reflection off the far end and then again at the initial tap end and again and again to build up a resonance. The frequency of such a resonance would be about $\frac{1}{2T}$, where T is the initial traversal time. All this would be true even if the cylinder were long and thin. But long and thin opens another possibility. Coil that thin cylinder into the shape of a spring. There will still be compressional waves that travel as just described from one end

to the other within the steel, along its length. But there is now, in addition, a new, very important kind of motion: the compression of the spring. In terms of the steel cylinder, the spring compression is a flexion (i.e., bending) of the cylinder. The speed of the spring compression waves is much slower and depends on the details of the spring shape.

The speed of sound in hardwoods is about 13,000 ft/sec, about ten times faster than the speed of sound in air, 1125 ft/sec. The time required for a compression pulse to traverse $3/4''$ of wood is about half a millionth of a second (0.5×10^{-6} sec). The frequencies of resonances within the wood are roughly 2 MHz and above. These are instantaneous and irrelevant, respectively, in the context of audible sound. Equivalently, the shortest wavelength in wood of an audible frequency is much bigger than any bridge dimension, again suggesting that shape is irrelevant for (compressional) sound conduction. And these facts have nothing to do with the details of the shape of the wood — at least for shapes realized in banjo bridge designs.

The first non-trivial aspect of the banjo bridge as it connects strings to the head is its extent in terms of footprint. In particular, in addition to delivering up-and-down vibrations, the bridge can rock. That just means that the outer feet need not move in phase as they are driven by various strings. However, the string motion is still transferred directly and essentially instantaneously to the head. More correctly, the bridge can be considered as an ideally rigid block of a certain mass and size, and that determines how it moves under the contact forces with the strings and head. So the footprint, particularly the outer reaches of the feet, and its position on the head, impact how the head will move in response. (Note: banjo bridges rock from side-to-side. Front-to-back rocking occurs but doesn't do anything appreciable to the head. In contrast, front-to-back is an important part of guitar bridge action because of the rigid mounting to a saddle.)

If the bridge is something other than a solid block, its flexural motion might be relevant. The traversal time of flexural waves and their resonant frequencies could be relevant to acoustic scales. This is the case to a small but discernible extent with violin bridges, where the flexibility of the design does have a small impact on timbre. However, violin bridges are far taller, thinner, and relatively more flexible than anything mounted on banjos. Banjo bridges have not as yet been studied from this perspective.

NOTES

[1] D. Politzer, *Banjo Bridge Mutes*, HDP: 15 – 01, www.its.caltech.edu/~politzer

[2] D. Politzer, *Simple Anti-Tone Rings for the Banjo*, HDP: 15 – 02, www.its.caltech.edu/~politzer

[3] D. Politzer, *The Open Back of the Open-Back Banjo*, HDP: 13 – 02, www.its.caltech.edu/~politzer

[4] The assumption of linearity is common to virtually all acoustical science, and it is almost always a very good approximation. Furthermore, only very limited progress and understanding is gained in situations where going beyond it necessary. And some sort of approximation is always a part of physics — otherwise, there'd only be one physics problem.

[5] D. Politzer, *The plucked string: an example of non-normal dynamics*, HDP: 14 – 04, *Am. J. Phys.* **83** 395 (2015), doi:10.1119/1.4902310 or www.its.caltech.edu/~politzer; *Zany strings and finicky banjo bridges*, HDP: 14 – 05, www.its.caltech.edu/~politzer

[6] J. Summers, *The True Story behind Taylor's Pallet Guitar*, www.guitaradventures.com/taylor-pallet-guitar-story; M. Simmons, *Taylor Guitars*, PPV Medien (2005)

[7] K.C. Wali, *Cremona Violins: A Physicist's Quest for Secrets of Stradivari*, World Scientific (2009); J. Marchese, *The Violin Maker*, Harper (2008)

[8] e.g., https://www.youtube.com/watch?v=G-lN8vWm3m0

[9] C. Fritz, J. Curtin, *et al.*, *PNAS* **109**(3), 760 (2012), doi: 10.1073/pnas.1114999109; in fact, Joe Curtin, who built the violin with the distinction of fetching the highest price ever paid for a living luthier's was quoted as saying he'd always taken it for granted that Strad's sound better than anything made in modern times.

Bridge recording identifications

bridge-1.mp3 = spruce; 2 = mahogany; 3 = walnut; 4 = bamboo

heavy maple = 5; light maple = 6