A Bacon Tone Ring on an Open-Back Banjo

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Head taps on a new Goodtime banjo rim fitted with a reproduction Bacon Professional ff tone ring are contrasted with a new Goodtime, a 2002 Goodtime, and a 1999 Goodtime fitted with a 1/4″ diameter brass ring. Conclusions: The 1/4″ ring does what's commonly imagined, the upgrades to the Goodtime over the years are not merely cosmetic, and the Bacon ring's biggest effect is to *damp* head ringing and *suppress* high harmonics. Detailed comparisons of the new Goodtimes with and without the Bacon ring suggest simple physics accounts of the differences. Conjectured mechanisms are energy dissipation by the vibrations of the Bacon horizontal flange, the added radial stiffness due to that flange, and the friction of air passing through the narrow flange-head gap.

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I. INTRO & OUTLINE

This note reports a small part of an on-going inquiry into the Bacon internal resonator banjo. Bacon's original design[1] of what became his "Professional ff" model included a particular tone ring. However, I was surprised by aspects of the ring itself. So, that ring is demonstrated and discussed here without the full internal resonator.

Head taps with a piano hammer are recorded for four different pots (no strings or neck), all with the same new heads (made-for-Deering Remo), set at the same tensions, and producing the same fundamental pitch.[2] The pot of interest is a new Goodtime fit with a new, reproduction Bacon ring.[3] The most relevant comparison is to a stock new Goodtime. Surprised by the outcome, I also compared it to a simple 1/4″ diameter brass tone ring. Since even that requires some rim wood removal, I chose to use an old one (made in 1999), already turned down, rather than altering another new one, just for that purpose. And that suggested including an old, unaltered Goodtime in the comparisons. Those are the pots in the title page photo.

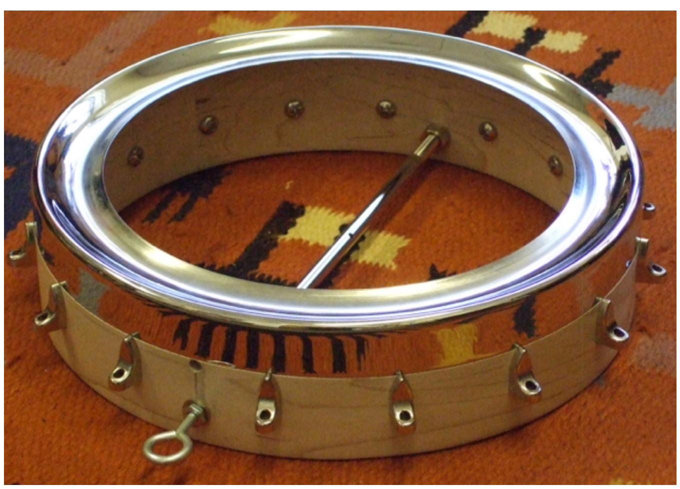

FIG. 1. A Goodtime rim fitted with a Bacon tone ring

The sound file in section **II** is a sequence of head taps for each pot, starting at the center and moving steadily out to the rim. I then present more quantitative comparisons of just the two new rims. Spectrograms represent frequency power as a function of time. This is closer to our hearing experience than a total-time spectrum. I conclude with speculation about the physics of the Bacon ring that is likely responsible for the differences.

II. HEAD TAPS — AUDIO

The sound of a banjo comes from the vibrations of the strings pushing on the bridge, which pushes on the head, which then moves air. Tapping the head with a piano hammer is a proxy for the string-bridge system. It allows us to focus on aspects of the head's response to those pushes. Any tap will excite virtually all possible modes of head motion.[4] However, varying the location of the tap puts different amounts of energy into different modes. This is analogous to plucking a string at different positions. (Nearly) all string modes will be excited by any one pluck, but moving closer to a fixed end puts more energy into the higher frequencies. Taps near the center of the head put the most energy into the lowest mode — and also into the other circularly symmetric modes. Taps near the edge excite higher modes more effectively, including the "azimuthal" modes (i.e., ones with head diameters among their node lines).

In the following sound clip, each of the four rims has the same model new head, tightened to the same tension. Each rim is suspended from an eyebolt screwed into the coordinator rod, in place of a neck. The backs are left wide open to the air. For each, you hear a sequence of taps that start at the center and move gradually out to the rim. The order of the pots is: 1) an old wood rim, 2) an old wood rim fitted with a 1/4″ diameter brass ring, 3) a new wood rim, and 4) a new wood rim fitted with a Bacon tone ring.

The Sound of Head Taps: If you're Web-enabled, the following link might be live; otherwise it should be retrievable.

http://www.its.caltech.edu/~politzer/bacon/four-heads-center-to-rim-wide-open.mp3

My own impressions: Each sequence begins with a tap at the center. These produce similar pitch and timbre. As the taps move outward, a ringing sound develops, not unlike the sound of a cymbal. The 1/4″ brass enhances the cymbal sound of the old wood, while the new wood (with no tone ring) has a cymbal sound that is even stronger than the 1/4″ brass on an old rim. The Bacon ring is somewhat muted from the start, sounding something like a thud, and it is relatively muted in its cymbal sound. Nevertheless — or perhaps very much on purpose — this ring design was the choice of Fred Bacon, a virtuoso performer in his time and a banjo design innovator. Of course, the tone ring was not meant to be there by itself but, rather, be an integral part of the internal resonator assembly.

The 1/4″ brass ring performed as commonly expected. It reduces the absorption of head vibrations at the rim and is more effective at that with increasing frequencies. Hence, it makes the banjo louder, with greater sustain and a brighter sound. I included it in the comparison because the Bacon ring contains a 1/4″ solid ring as its core. I imagined that any metal tone ring would produce the same general effects and wanted to explore how the extra Bacon flanges that wrap the 1/4″ core affect the sound. The sound of the newer Goodtime rim as compared to the old one reflects its being harder and stiffer — even though both are wood, with the same dimensions. The newer rim has harder wood and better construction. The surprise was the thud of the Bacon ring, in comparison to the others, and its weaker cymbal-like sound.

III. A WARNING & APOLOGY IN ADVANCE

The many pages before you end with no simple, convincing conclusion. Several methods produce sounds for graphic display. However, the connection of those efforts to how things sound to us and/or to the mechanics of sound production remains somewhat murky. With regard to mechanisms, there are some candidates. They suggest general trends but also include dramatic variations (e.g., at particular important resonances). For the most part, those mechanisms seem impossible to separate experimentally through mechanical strategies. So connecting the physics ideas to the actual sound would require combining the several competing mechanisms, each evaluated with considerable accuracy, using the actual parameters of the instrument. Failing that, I simply offer my perspective. There are no equations and no triumphal comparisons of theory and measurement.

It is sometimes remarked that the presence of many explanations reflects the absence of any single good one. You were warned.

IV. GOODTIME RIMS

The original Deering Goodtime, introduced in 1996, had an 11-ply rim. In 2008, they changed to a 3-ply solid maple rim. My "old wood" rim is unmodified 11-ply, and the "1/4″ brass" has a brass ring fitted to an 11-ply rim. "New wood" refers to a 3-ply current production model, and the Bacon ring was fitted to a second, new, 3-ply rim.[5]

V. THE BACON TONE RING

FIG. 2. The Bacon tone ring, as currently produced by Stewart-MacDonald

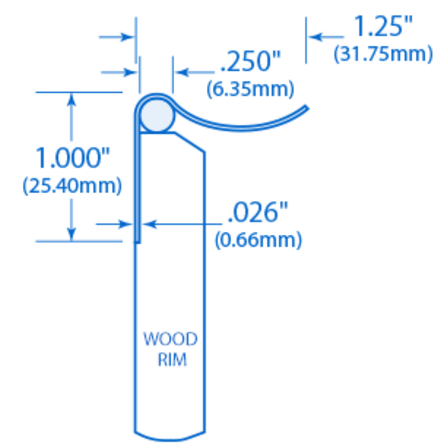

FIG. 3. Cross section specs of the Stewart-MacDonald Bacon ring

FIG.s 2 and 3 illustrate the Bacon ring currently sold by Stewart-MacDonald. That's what I used. Bill Rickard of Ontario, Canada also sells one.[3] As shown in FIG. 3, there is a 1/4″ diameter solid ring that is over-laid with a 0.026″ thick sheet of brass. (Stew-Mac's are nickel-plated; Rickard offers both plated or raw.) The inner edge of the concave-upward horizontal flange formed by that sheet comes within 1/8″ of the under surface of the head. I believe that the solid ring of the Stew-Mac model is steel, and Ricard's is brass. The top edge of the stock Goodtime rim has an outer 1/4″ diameter half-round and then is flat for the inboard remainder of the rim thickness. To fit the Bacon ring, 1/4″ has to be removed from the top and a small amount removed from the outer surface to allow a good fit of the ring's outer skirt. Beveling the remaining part of the rim top is traditional (as shown in FIG. 3) and may well have acoustic consequences. The rim used here has such a bevel.

The 1/4″ solid ring is not attached to the outer wrapping — at least on the one I used. It just sits there. However, when the pot is fully assembled, the down pressure of the tightened head is sufficient to make the pot move as a single, albeit flexible, piece. (When disassembled, there is a very shallow indented groove formed by the 1/4″ rod embedding itself slightly into the hard maple of the rim.)

The relation of the currently manufactured tone rings to Bacon's originals is a fascinating story in itself. Bacon formed a company to produce and market his internal resonator design 5-string banjo. Much of the work was contracted out to well-established banjo manufacturers. Sometimes that was whole banjos; sometimes it was parts; and sometimes his crew made some parts themselves. No single design was strictly adhered to. Surviving examples show variations in cosmetic and structural details. All versions had some sort of internal resonator, i.e., a partial back and a partial wall that defined an internal annular volume. The common feature of the metal tone rings was the single piece of thin metal that formed their horizontal and vertical flanges. That thin piece was supported by some sort of core, but the cores differed. I suggest below that it is the horizontal flange that contributes the characteristic behavior.

There is no extant official version of the Bacon Co. history. In recent years, several people have tried to sleuth it out.[6]

VI. HEAD TAPS — SPECTRA & SPECTROGRAMS

One measure of loudness is the sound power produced by the strongest resonant mode, averaged over a few dozen taps. In these tests, the fundamental was the strongest single peak in the spectrum — by about 12 dB for taps near the edge, recorded in front at 24″. (My individual taps varied by less than ±2 dB from their average.) Judging by the fundamental mode peak, when tapped near the edge, the loudest rim is the new wood, while the fundamental of the Bacon ring is just 1 dB lower, a difference comparable to the resolution of the measurements. The fundamental peak of the old rim with the 1/4″ brass ring is down 4 dB from the new wood. The bare old wood rim is down 6 dB from the new one.

Since the goal here is to characterize the Bacon ring, I focus on the new Goodtime rims, with and without the Bacon ring.

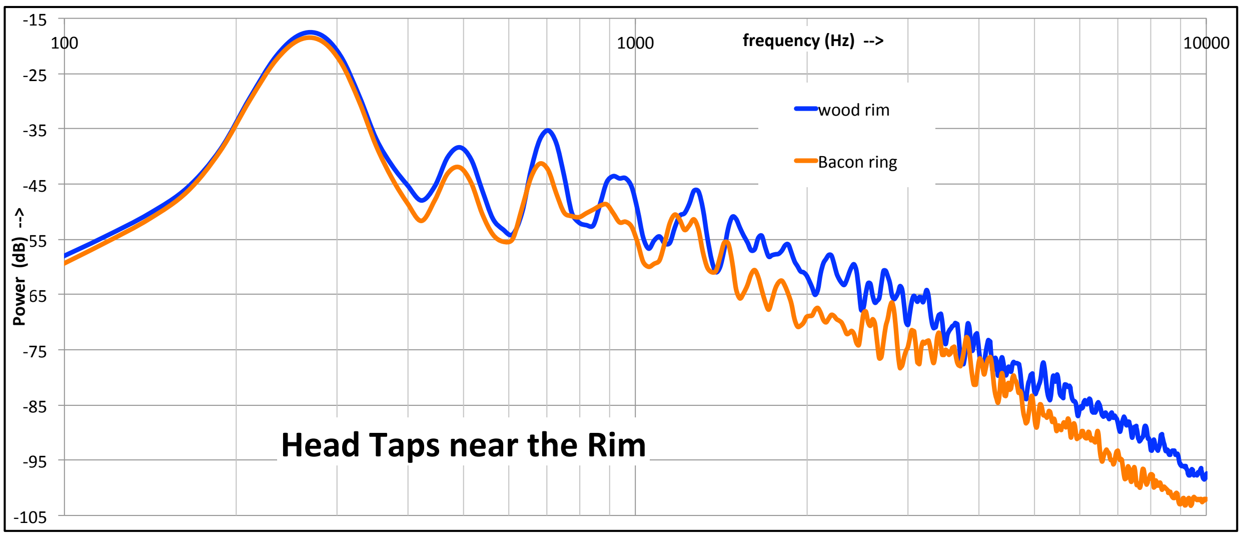

FIG. 4. Spectra averaged over a few dozen head taps near the rim

FIG. 4 shows the frequency spectra for head taps near the rim, comparing a new, stock Goodtime ("wood rim") to a new one with a Bacon tone ring installed. Two technical comments are relevant. 1) The calculation of any such spectrum from a recording (done here by Audacity software) involves choosing an evaluation time interval window of some particular length and shape. That impacts the frequency resolution of the output. I chose the one that best illustrates the point in question. And, of course, it's the same choice for the samples being compared. One awkward feature is that the resolution is a fixed interval in frequency — and not in the logarithm of the frequency. And 2) the spectrum is evaluated for the whole time interval of the sound – in this case, a set of forty taps. Identical spectra can result from totally different sounds.

The peak of the fundamental mode is at 268 Hz for both pots, with the Bacon ring apparently reducing that peak by just 1 dB. However, starting at about 400 Hz, the Bacon ring results in a suppression of what is often about 4 to 8 dB. But the sounds are very different — in ways other than what's apparent from the time-averaged spectra.

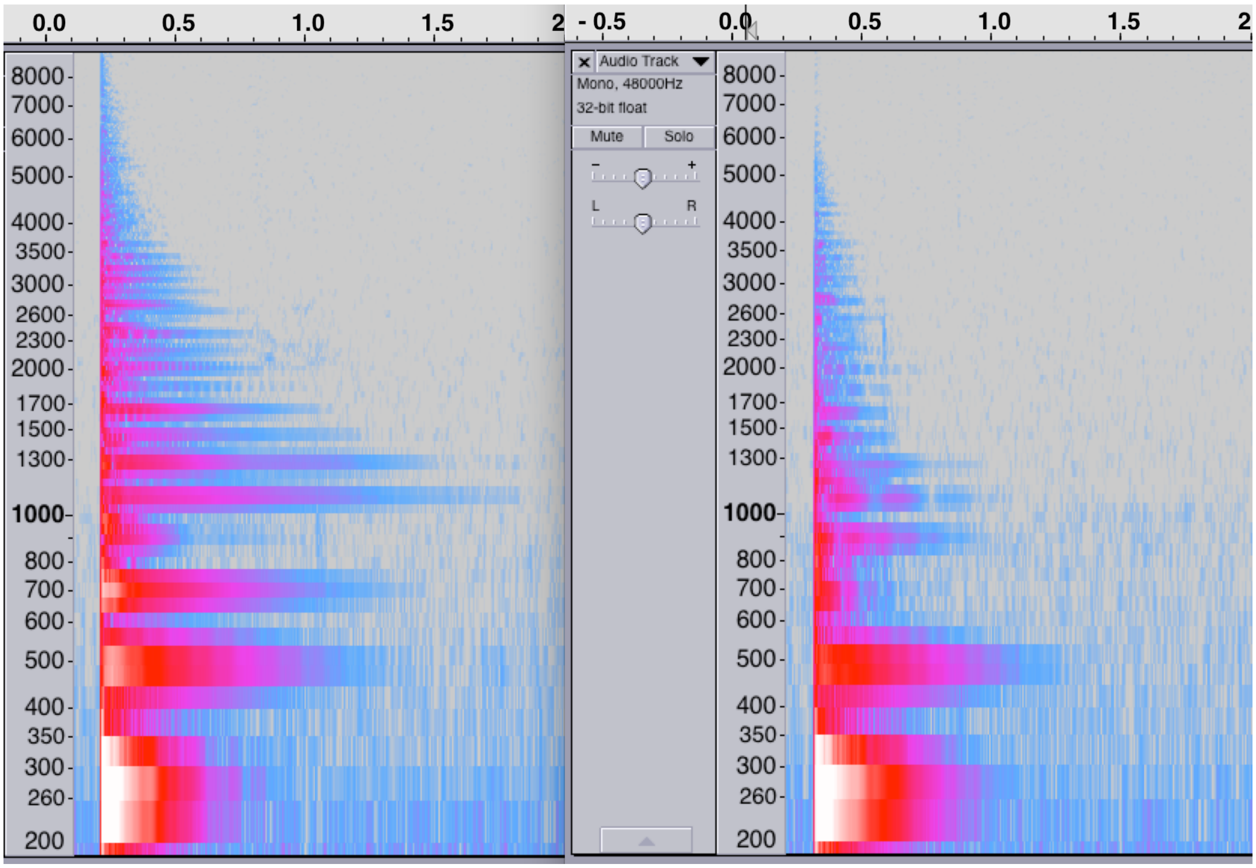

FIG. 5. Typical head taps near the rim for the wood rim (left) and Bacon ring (right); the horizontal scale is time in seconds; the vertical scale is frequency in Hz. Intensity decreases from white to red to magenta to blue (to grey), with each basic color band corresponding to an interval of 20 dB.

Spectrograms offer an alternative analysis which is closer to how we actually hear. Two representative single tap sounds are analyzed in FIG. 5, from the stock wood rim on the left and from the Bacon ring rim on the right. Time flows horizontally to the right, with a legend in seconds indicated on the top. Frequency in Hz is on a log scale from bottom to top. And colors and their intensities are used to indicate the power (in dB) for a particular time interval and frequency band. (So, viewing in color is essential.) Here, the fundamental colors were chosen to be 20 dB apart. The evaluation of frequency spectra, now as functions of time, again requires a compromise and trade-off in resolution. Sharper in time requires broader bands in frequency and *vice versa*. This is an example of the fundamental Uncertainty Principle.[7] Again, different choices can highlight different aspects of the sound.

From FIG. 5 we see that the sound from the fundamental mode is very similar for the two, with the Bacon ring lasting just a bit longer. Starting at 500 Hz, the two begin to differ markedly. Not only is the Bacon ring weaker, it dies off faster. Furthermore, the relative strengths of the harmonics at different times are quite different for the two pots. This is the spectrogram's representation of the fact that the timbers are different and develop differently in time.

A typical feature that is apparent in FIG. 5 is that some of the frequency bands show beats, i.e., get louder and softer with a fairly regular periodicity. This is not a particular distinction between the two pots, but I think it's of general interest. The phenomenon arises because energy can transfer back and forth between motions of nearly the same frequency but with different efficiencies of producing sound.[10] Its appearance in a spectrogram depends on the resolution choice. Poorer time resolution will smear out the loud-soft variations. But better time resolution yields poorer frequency resolution, which smears out a frequency band by combining with adjoining bands which might not have beats with the same frequency. I made a choice for FIG. 5 that best conveyed the relevant story. Our ears effortlessly can do better.[9]

VII. RESONANT *VERSUS* "REVERBERANT"

FIG. 6 shows the same two plucks as FIG. 5, but only for the frequency interval 1000 to 1300 Hz. Furthermore, I used sharper frequency resolution — thus sacrificing some detail in the time evolution. (For example, some of the beating visible in FIG. 5 around 1200 Hz is no longer apparent.) The single strike of the piano hammer has the potential to excite any frequency of head vibration — at least over a reasonable range. And over the range displayed, that "potential" is certainly almost constant. That is reflected in the general produced-sound response, common to both pots. All frequencies are present at roughly similar strengths, lasting about 0.4 seconds. A few particular head resonances stick out from that general response. However, the all-wood rim response has resonances that are louder at the outset, are more sharply defined in frequency, and last longer in time. Even excluding those resonant frequencies, the all-wood rim exhibits greater variation in intensity *versus* frequency than the Bacon ring.

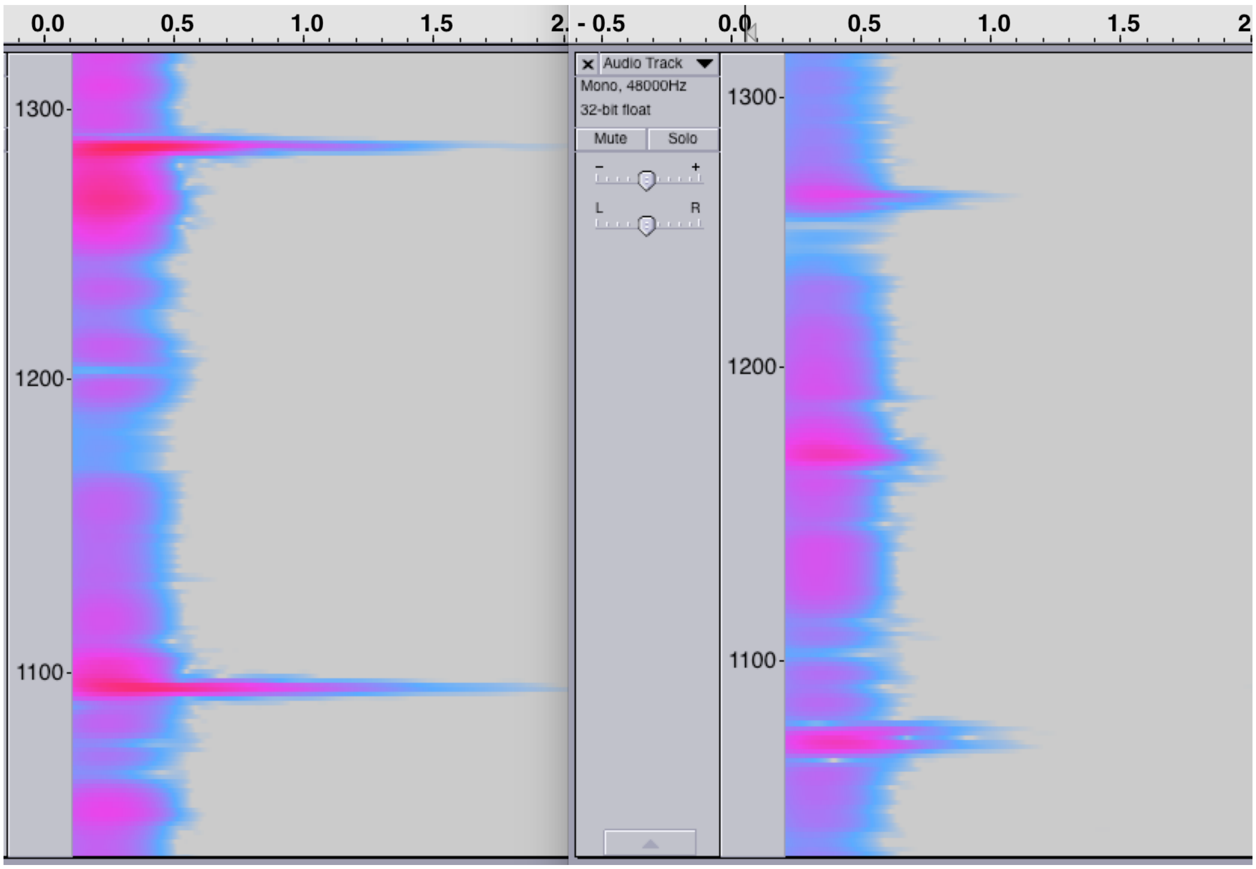

FIG. 6. Blow-up of ∼1000 to 1300 Hz of the same two recorded plucks as displayed in FIG. 5 with higher frequency (and worse time) resolution — wood rim (left) and Bacon ring (right)

One feature of a fine musical instrument is that it should not be difficult for the player to keep the sound of particular notes from jumping out. Somewhat more subtle but no less important to people with good ears, the voice or timbre of the instrument, if not uniform over its whole range, should change imperceptibly from note to adjoining note and be compatible (somehow) over the entire range. To focus on this issue, some acousticians give special, technical meaning to the terms "resonant" and "reverberant." Resonant suggests the presence of resonances. If the listener can hear them individually, that's a problem. Reverberant suggests an even response of the instrument for different frequencies. This applies not just to the fundamental frequencies of the played pitches but also to all their higher harmonics. Fred Bacon presumably had a good ear, and there are certainly people among contemporary banjo players who do likewise.

VIII. STRING PLUCKS — SPECTRA & SPECTROGRAMS

With neck and strings mounted, I recorded single plucks of the open first string. All strings were left undamped, and my research-grade synthetic belly[11] was mounted to provide a reproducible approximation to normal open-back playing. Judged by the record of microphone voltage *versus* time, it was easy to produce a long string of nearly identical plucks.[12] Differences in the resulting spectra and single pluck spectrograms show features reminiscent of the head taps, albeit a bit more subtle.

As shown in FIG. 7, the power spectra evaluated over the full length of a few dozen plucks are rather similar with and without the Bacon ring. To the extent that they are different, there is no suggestion of a single, simple underlying cause. However, close examination reveals a faint echo of the tap-derived spectra. There are regions of frequency where one is systematically stronger than the other, matching the head tap behavior. For example, above 1000 Hz, the Bacon ring gives a suppression — *except* around 1500 Hz, 3000 Hz, and 4000 to 6000 Hz.

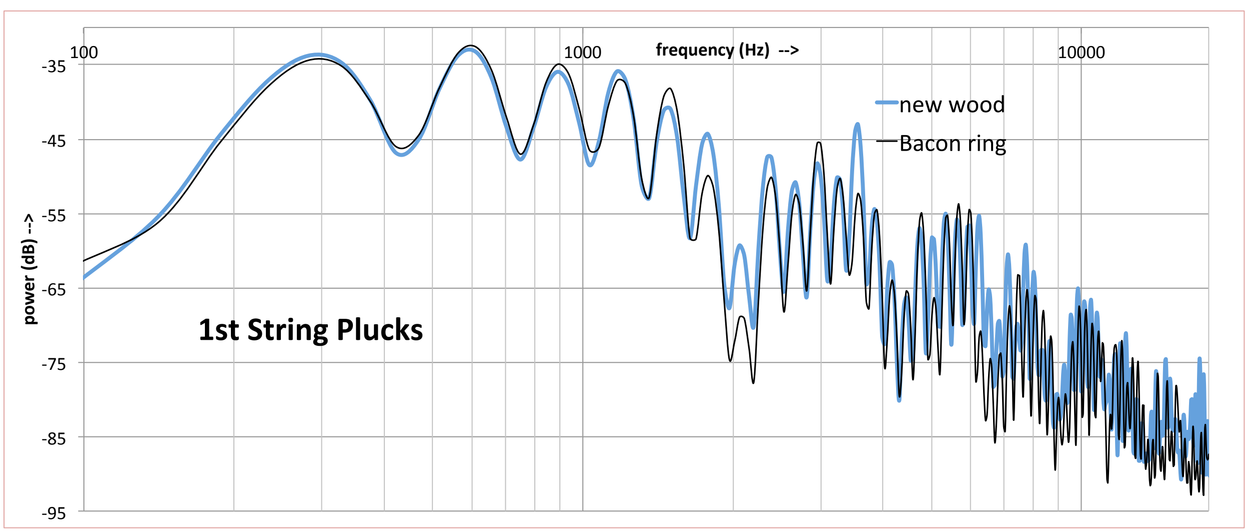

FIG. 7. 1st string pluck spectrum, with all strings open

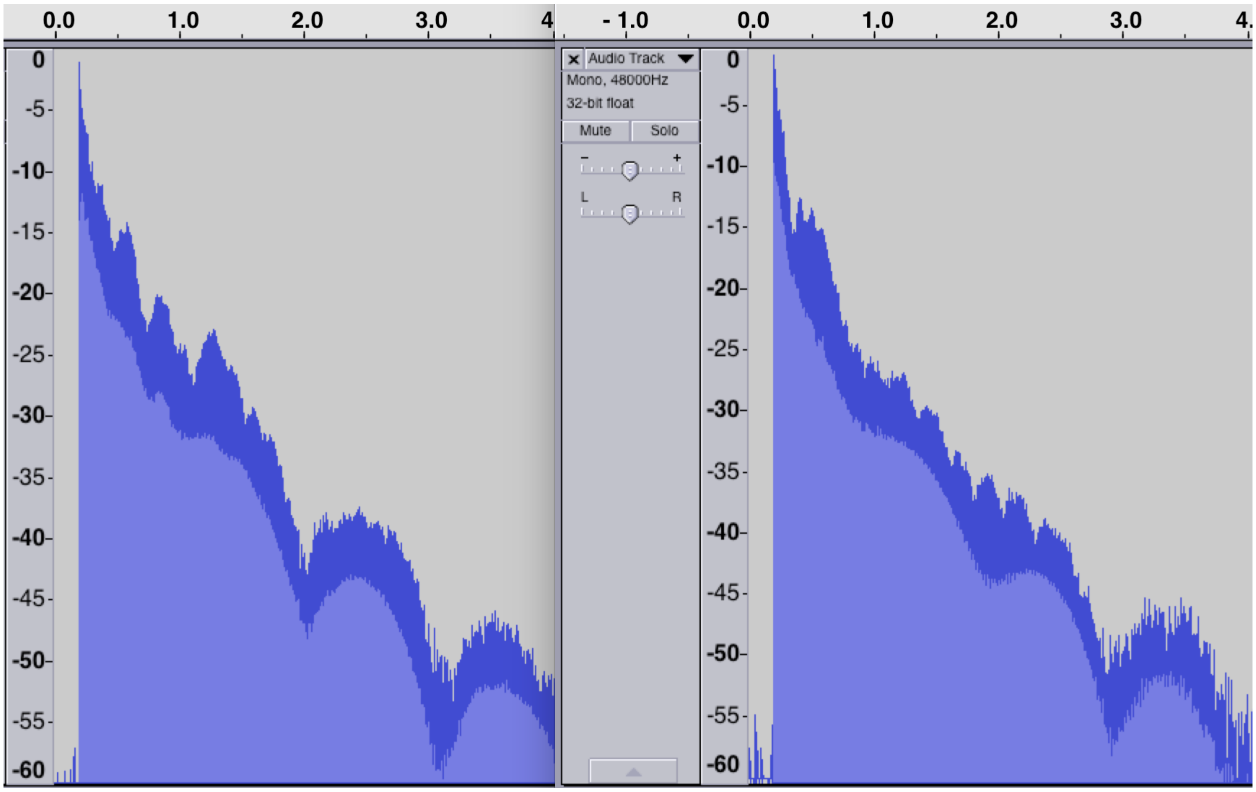

FIG. 8. Signal amplitude, plotted vertically in dB, of representative 1st string plucks — new wood on the left, Bacon ring on the right. Time is horizontal in seconds. .

The time between successive notes in normal playing is typically something like 0.1 to 0.5 seconds. FIG.s 8 and 9 show longer times in hope of identifying some differentiating features.

Individual oscillations of the microphone voltage are too fast to appear in FIG. 8. The upper edge of the dark blue region represents the envelope of successive maxima. Because the amplitudes are represented on a (logarithmic) decibel scale, pure exponential decay would be represented by a straight down-sloping line. The amplitude envelopes decay similarly for the first 0.10 seconds. After that, the Bacon ring power generally falls off a bit faster than the bare wood.

The spectrograms of FIG. 9 look similar, but subtle differences can be identified. You just have to look closely, comparing corresponding harmonics at corresponding times. Many (though not all) harmonics are stronger and last longer with the wood rim. (The plucks compared in FIG.s 9 and 10 are the same two as displayed in FIG. 8.)

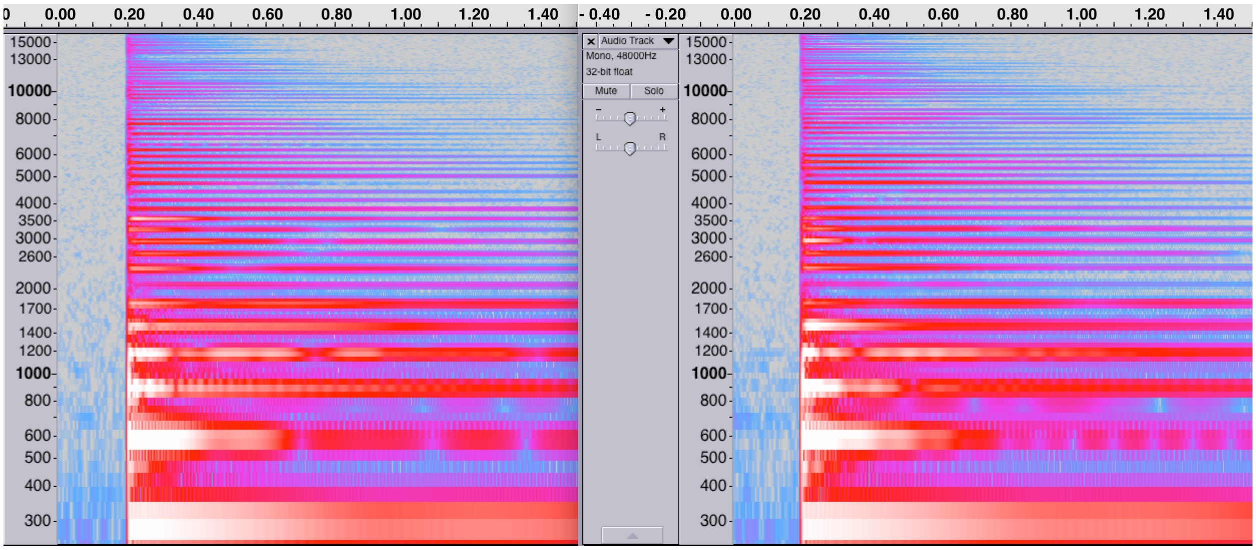

FIG. 9. Spectrogram of representative 1st string plucks, new wood on the left, Bacon ring on the right. Time is horizontal in seconds – about 1.2 seconds total. Frequency is plotted vertically in Hz. The intensity color scale is the same used in FIG. 5, 20 dB per basic color.

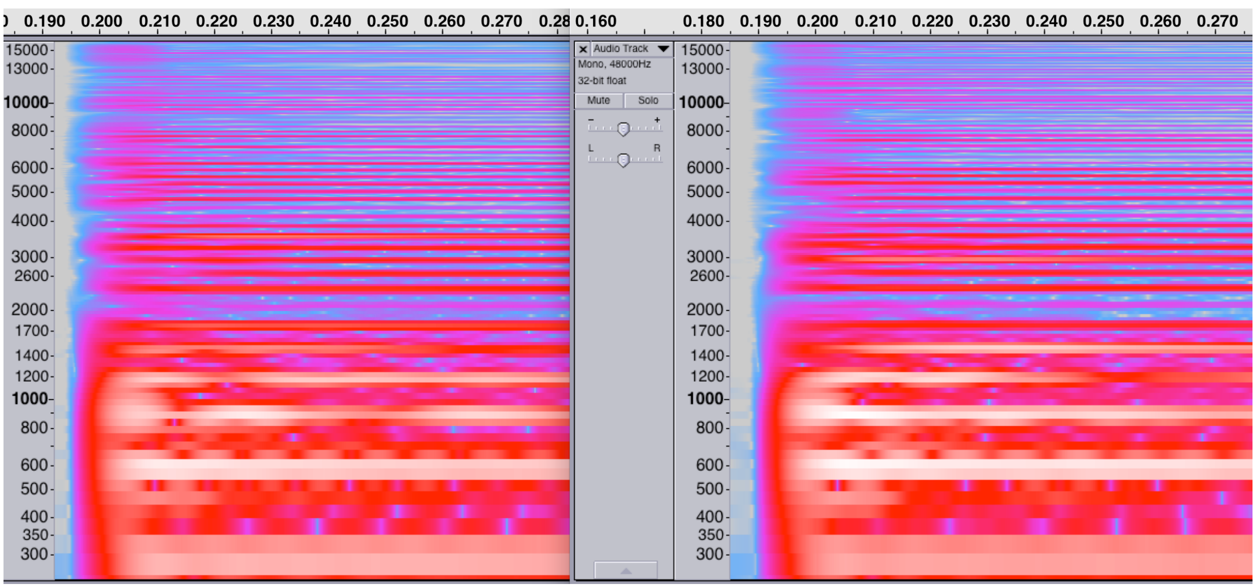

FIG. 10. The initial 0.09 seconds of a spectrogram of representative 1st string plucks, new wood on the left, Bacon ring on the right. Frequency is plotted vertically in Hz. The intensity color scale is adjusted to 12 dB per basic color.

Audacity offers a huge number of alternative settings for the spectrogram calculation and view. For example, the time scale can be greatly expanded to view the attack in detail, as in FIG. 10. As discussed previously, there is the trade-off of frequency and time resolution, but one can select different ranges of frequency to display and select different sensitivities for the color representation of intensity. However, I could not find any choice that made differences between the rims any clearer.

IX. EXCEPTIONAL OR GENERIC?

The comparisons presented above involved one particular tone ring installed on one rim. One might ask whether it was a lemon or somehow incorrectly installed. To check this, I tested three different Stewart-MacDonald rings mounted on two different, new Goodtime rims. There were no systematic differences between them.

Of course, comparisons of recorded sounds are only relevant if done under as identical circumstances as possible. Some details of the recordings may reflect positioning of the instrument, microphone, and furniture in the room and possible tuning and muting of the head and strings. What is most telling in the recordings and various graphs presented here are the differences, presumably attributable to the intentional differences in the instruments.

X. HEARING, PLAYING, PLUCKS, & TAPS

Our ears and our sub-conscious analysis of their sensory input are exquisitely sophisticated. Without necessarily being aware of the effort, we pay attention to many aspects at once, and not only to the sound of the immediate input but also in comparison to what came before — very recently, not so recently, and even in the distant past. We end up with a mental picture of what we're hearing. In contrast, when we look at a microphone voltage trace, a spectrum, a spectrogram, etc., we consciously try to relate their details to our impressions of the sound — and we're not very good on issues beyond the very obvious. This is why some artificial means of stimulating sound production sometimes serves to highlight issues and differences whose origins we may wish to understand. In the case at hand, the head taps do just that. They lead to sound production by the same mechanism as playing the strings, i.e., they push on the head at various frequencies. The differences observed with individual plucks are apparently not nearly as evident as with head taps. And they're less evident in normal playing. And, even when normal playing gives an impression of differences, many of us are challenged to find words to communicate of the differences we hear. But there is no reason to wonder whether the observed head tap distinctions also appear in normal playing. They must. It's just a question of how evidently. And that depends a lot on your own hearing. I found the difference to be more evident when I plucked than when I frailed. (My frailing tends toward full chords rather than single notes). So here are two mostly plucked sound samples, with my own perceptions relegated to footnote [13].

As before, if your reading is Web-enabled, the following link might be live; otherwise it should be retrievable. On the new wood rim:

http://www.its.caltech.edu/~politzer/bacon/Last-Singing-new-wood.mp3

And, with the fitted Bacon tone ring:

http://www.its.caltech.edu/~politzer/bacon/Last-Singing-Bacon-ring.mp3

FIG.s 11 and 12 show the spectra for the full ∼50 second recordings. The 100 to 1000 Hz of FIG. 11 has high enough resolution to see separate peaks for the various pitches and their harmonics. FIG. 12 covers 100 to 20,000 Hz at lower resolution. This averages over the individual peaks until very high frequencies (again because the resolution is a fixed interval in frequency and not in the logarithm of frequency). FIG. 12 actually matches FIG.s 4 and 7 rather well in its basic message of the Bacon tone ring suppression and enhancement as a function of frequency, supporting the validity of head taps and single plucks as useful diagnostics.

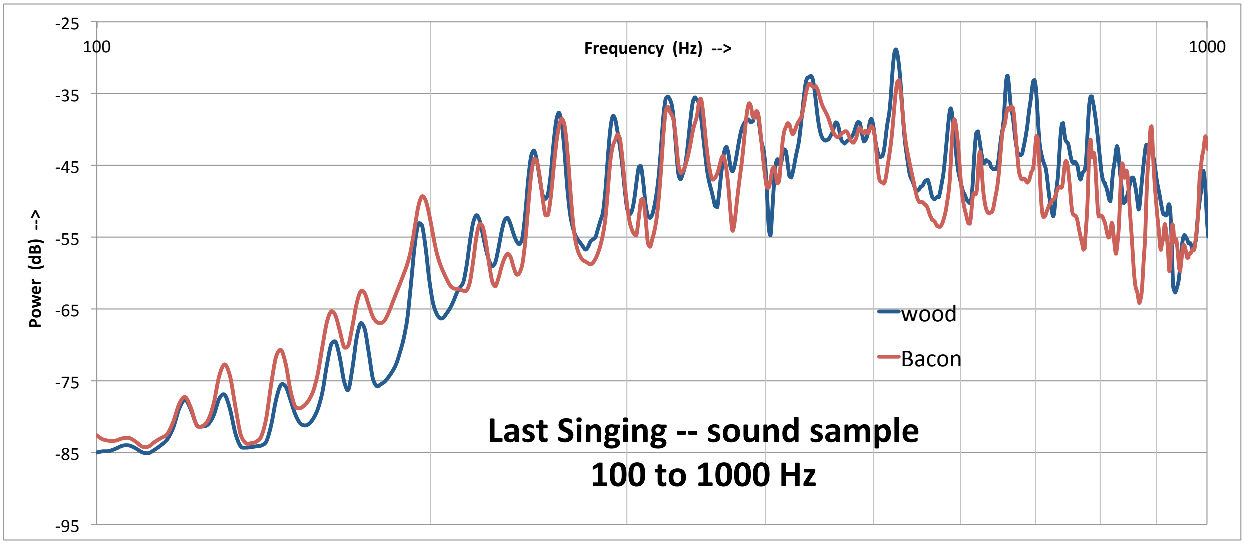

FIG. 11. Full length, high resolution comparison of the two sound samples

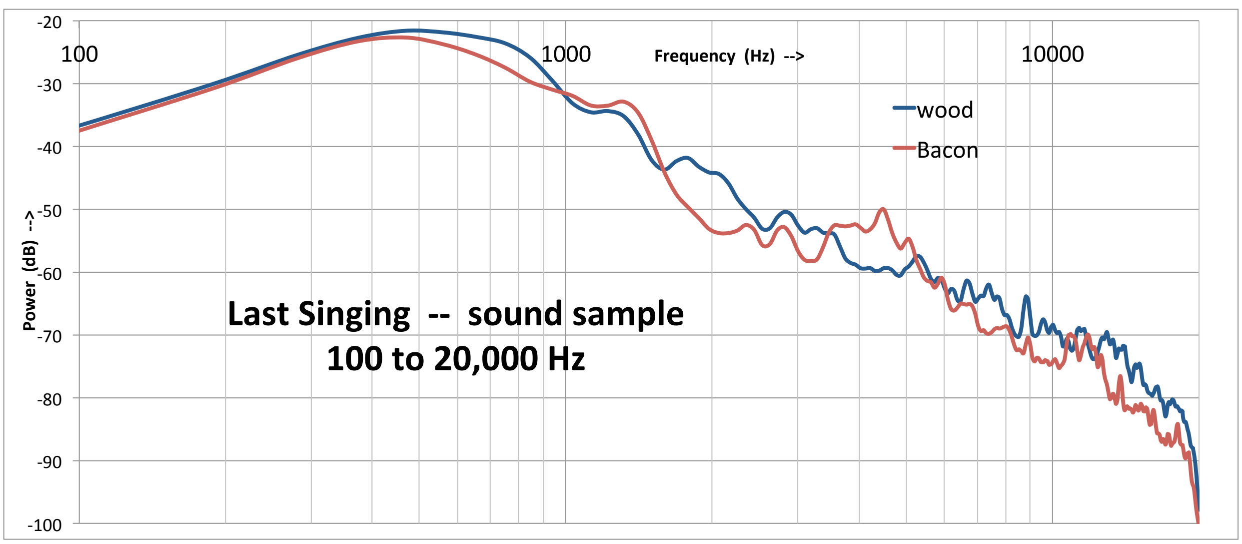

FIG. 12. Full length, low resolution comparison of the same two sound samples

XI. PHYSICS SPECULATIONS

Adding the Bacon tone ring is a single modification in terms of construction. In terms of physics, it involves several conceptually distinct mechanisms that potentially modify the sound. Observing each of those mechanisms separately would require far more sophisticated sensors and instrumentation than simply recording the total sound. Multiple different versions of the tone ring, covering ranges of its parameters, would help clarify the actual effects.

Understanding those effects in terms of models, equations, and actual numbers would require computer computations on a scale normally only attempted when large amounts of money are at stake. Well aware that it is easier to ask questions than answer them, I simply sketch what's likely.

A. Two Crucial Aspects of Dissipation

A resonance corresponds to a particular motion that eagerly absorbs energy from its environment and then oscillates with particularly large amplitude. Musical instruments rely on resonances to define their particular pitches. All resonances loose energy, too. Producing sound is one of the possible ways. With a mechanical resonance, the rest of the energy goes ultimately to heat, produced by friction. Very rarely is sound more than a tiny fraction of the total energy loss. The ratio of sound energy production to the total energy loss — or sonic efficiency – can be a fraction of a percent or maybe even a few percent.

The banjo's head is its most efficient producer of sound. The head may transfer some energy to another part by making that part move. If the other part made no sound *and* dissipated no energy, that transferred energy would make its way back to the head. The net result of the transfers would make the sound of the head quieter but longer lasting. The action of string modes that "sing along" with the plucked strings are approximate examples of this phenomenon. Some string modes are better at transferring energy to the head than others, but none lose energy as fast as the head. String sound production and total energy loss are tiny compared to those of the head itself. But other banjo parts have serious damping as well as very inefficient sound production. Therefore, when a resonance in any part of the rim assembly absorbs energy from the head, the total production of sound will be *less* than had all the energy stayed with the head. Analogs of such damping by resonances has been used in architectural acoustics for centuries and in electrical devices for decades for reducing the amplitudes of particular ranges of frequencies.

A second aspect of dissipation commonly appears in numerical engineering calculations but is absent from simple physics expositions. (Physics teaching generally sticks to simple examples that can be worked out in detail by hand. That's not necessarily a bad thing. It's related to what it means to understand something.) The question is how fast can you get energy into the resonant system compared to the rate at which it dissipates that energy.

That depends both on the resonance physical parameters and on the nature of the coupling of the driver to the resonance. If you only have a limited time (as is the case with plucking a dissipative system), there can be potential resonances which never really get going.

B. Coupled Systems *versus* Parts of a Single System

There is an important distinction for which I neither know the precise criteria nor the appropriate terminology. At issue is whether it is enlightening to focus on sub-systems of some larger system. For example, a banjo is a single object, all of whose parts interact and potentially influence one another. However, it is useful to consider a single string and its own dynamics in isolation. Its ends are influenced by how they're attached. And those ends can drastically effect the resulting resonances. A familiar analogous example is blowing across the end of a pipe. Closing the other end lowers the pitch of the blow sound by an octave, i.e., cuts the frequency in half. But we analyze the air in the pipe with the same equations for the open and closed end versions, only at the end (of the calculation) addressing the effect of the end (of the pipe). With the string, except for the end points, each point along the string is only directly influenced by its neighbors, and, in the simplest cases, the form of those influences is the same for every point along the string (again, except for the ends). Similarly, the exceptional points of the head are those in contact with the bridge or the rim. All other points only see and feel their neighbors and act accordingly.

The rim, tone ring, and head tensioning apparatus present a different story. (The tensioning involves a tension ring, hooks, and a ring at the edge of the head, historically called the "flesh hoop.") When assembled properly, the contact surfaces of these items move together, i.e., without any relative motion. The extent to which it is useful to consider the components separately depends on what we ask.

Consider the tone ring. Even if its contact surfaces with the head above and wood rim below are held perfectly still, its horizontal flange can wiggle. The material of the flange can move up and down in waves that go in the "around direction." At very much higher frequencies, there can also be wave motion of the flange in the in-and-out direction. (Direction labels are defined in FIG. 13.)

For the wood rim itself, there are possible motions for which the head, tone ring, and tension ring are a constraint only on the top edge. Below that, the rest of the wood can

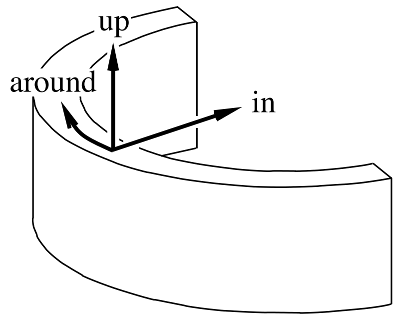

FIG. 13. Defining directions relative to the rim

wiggle. The lowest frequency modes of this type involve in-and-out motion of the rim with the wave motion in the up-and-down direction and a node line all the way around the rim, about half way up. In practice, these give only tertiary effects because bent, 5/8″ plywood is not going to flex very much in that way when driven by the head.

On the other hand, the lowest frequency modes of the rim are in and out with the corresponding waves in the "around" direction; there is no variation of the motion in the up-down direction. For these motions, any piece of the rim moves exactly as does the wood and metal directly above it. The equations which describe the around-going waves include the mechanical properties of all of those connected parts. The behavior of one of those parts on its own tells very little about the total assembly.

I am considering here only transverse flexural waves of the strings, head, tone ring, and rim. The only true longitudinal sound waves of primary importance are in the air. Longitudinal sound waves in the solids do influence the sound in the air — if one listens closely. Their first appearances are the longitudinal waves of the plucked strings, which add tiny bits to the highest frequencies of the audio range. But you have to start somewhere...

C. Flange & Rim Vibration

After lots of banging, tapping, and plucking, an obvious suspect was the horizontal flange of the tone ring. It stiffens the in-and-out motion of the rim, and it vibrates on its own in the up-and-down direction. The goal is to understand the difference between the original wood rim and the Bacon ring-fitted rim. But the starting conceptual point is the ideal rim, for which there is absolutely no motion at the edge of the head. Then we can ask how the Bacon ring differs from the bare wood.

[An aside: All four pots in the head tap sound sample of section **II** have a common geometry of how the rim falls away from the head as it goes inward from its contact circle. In particular, they all have the curvature of a $1/4''$ diameter round. People with good ears can actually hear the difference when that curvature is either sharper or milder. $1/4''$ is a traditional favorite. When it vibrates, the head actually makes contact interior to its equilibrium contact. But I'll stick with the $1/4''$ for this discussion.]

There is a sponginess to an all wood rim that absorbs and dissipates head vibrations at the contact edge. And a brass $1/4''$ tone ring allows less of that. Little, localized depressions are easier to form than long ones. So higher frequency azimuthal modes (i.e., the nodes with many head diameter node lines) show the biggest difference between wood and solid metal. In this respect, the Bacon ring is no different from the $1/4''$ brass.

Adding mass to the rim by replacing wood with metal also generally reduces the motion of rim in response to a given force. The $1/4''$ brass ring adds some; the Bacon ring adds more. The Bacon ring includes $0.026''$ thick flanges in the vertical and horizontal directions that increase stiffness in their respective planes. That increase in stiffness is far greater than would be provided by the same amount of metal in the form of a solid circular cross section. In-and-out motion of the rim with waves going in the around direction are clearly more important than going-around waves with the rim going up and down.

My own simple method has been to listen to and record produced sound. The initiators have been normal playing, individual plucks, hammer strikes, piezo drives, or electric speaker sound. None are quite up to the challenge at hand. Sophisticated acousticians of musical instruments have used laser interferometery for decades to image normal modes. These have contributed to general understanding of particular instruments. However, they're usually limited to a few lowest modes and are ineffective at distinguishing the subtleties that are of real interest to builders and players.

The relevant motions of the tone ring and rim involve those parts being rigidly connected to each other, to the tension ring, and to the edge of the head. So a proper test would involve the fully assembled pot, with rim, tone ring, and head firmly attached at playing tension. However, I failed to find a way to initiate sound that was not overwhelmingly dominated by head motion sound. The following describes a somewhat compromised alternative.

Headless Rim Taps

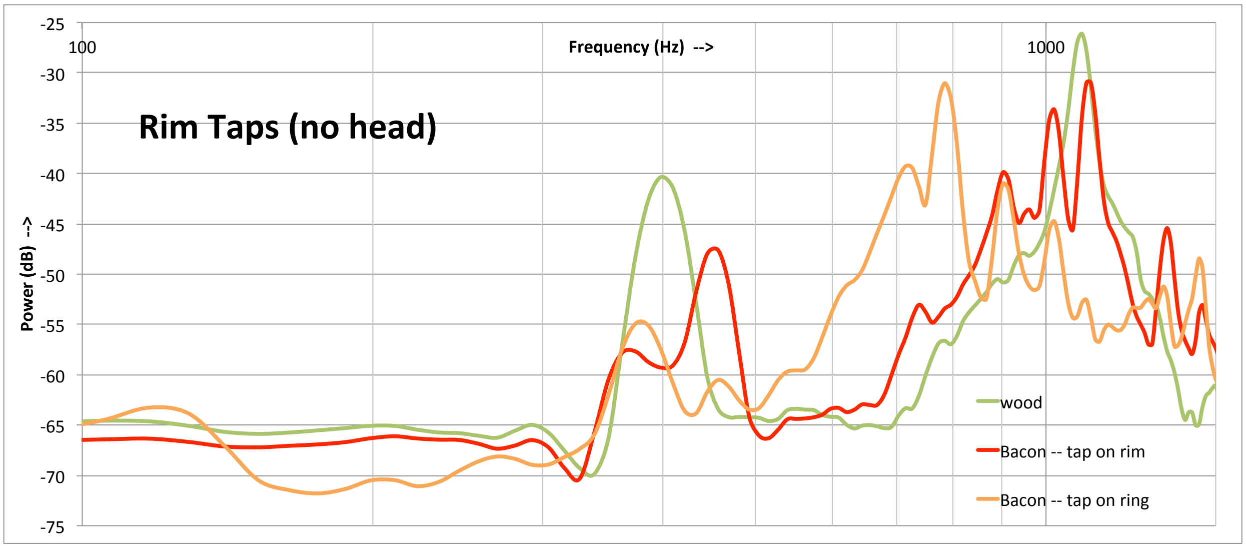

FIG. 14. Tapping the Bacon-equipped rim in different places to distinguish flange from rim motion

I compared the sounds of taps on a headless all-wood rim to one with a Bacon ring installed. This was only possible because of a fortuitous spell of high humidity. It rained and drizzled for a couple of weeks. What is a *very* snug slip fit in typical San Diego/Pasadena weather became *totally* unmovable at 90 - 98% relative humidity. Without the pressure of a tensioned head, the dry-weather slip fit allows enough acoustic frequency vibration between the ring and rim to render the same sort of measurement unintelligible.

It will help to visualize the lowest few vibrational modes of an ideal ring. The ring motion is in and out, and the wave motion is around the ring. The lowest frequency mode has four equally spaced nodes. Imagine hanging a ring from a thread, much as I did with the rims from their eye-bolts. The thread or eye-bolt is at 12:00 o'clock. Because both rims had their co-rods installed (see FIG. 1), the rim was very stiff between 12:00 and 6:00. So the lowest mode has nodes at 12:00, 3:00, 6:00, and 9:00. A tap at 1:30 gave the strongest lowest pitch sound, while a tap at 3:00 sounded weaker and higher. Higher modes involve successively more, equally spaced, diametrically opposed nodes.[14]

Tap sound frequency spectra are shown in FIG. 14. The wood rim fundamental is at 408 Hz. Tapping at 1:30, the strongest wood rim response is at 1085 Hz. I expected that in-and-out stiffening of the rim due to the horizontal flange of the Bacon ring would be more significant than its added mass. So each mode frequency (proportional to the square root of the stiffness divided by the mass) should be higher. The “tap on rim” trace shows the result of tapping on the Bacon-fitted rim. There is a peak at 452 Hz — but also one at 371. The resolution of this conundrum came with tapping directly on the horizontal flange. The same two peaks that appear in the “tap on rim” are also present in this “tap on ring” — but now with different relative strengths.

A single object has its resonant modes and their frequencies. The magnitude of their responses to some external stimulation depends on how you do it. This is very familiar in the case of the whole banjo. Hit one string, and you hear a note. Hit another string, and you hear another note. And that’s not mysterious. However, the complete list of banjo resonant modes is the same in the two cases. The vibration of un-hit strings can be faintly heard when some other one is hit. The same is true of the rim.

With the Bacon ring installed, there is no pure flange resonance that is distinct from a pure wood resonance. However, there is clearly a resonance that has a lot of flange vibration and one that does not. In fact, the flange vibrations peak at 786 Hz, and that’s the pitch you can hear loud and clear when tapping right on the flange. Going back to the two peaks on either side of the 408 Hz of the pure wood, the 452 is apparently mostly wood and, indeed, higher than the pure wood. The 371 Hz is a new possibility, not present for the pure wood rim, featuring strong vibration of the flange.

This is repeated elsewhere in FIG. 14, although not as unequivocally as around 408 Hz. The story that goes with the 1085 all-wood peak is almost certainly the same as with the 408.

The lesson from FIG. 14 is that in the region up to 1600 Hz, the all-wood rim has two prominent, relatively narrow resonances. The Bacon ring splits each of those in two and adds some more. The net result is more resonance spread more evenly over the whole frequency interval, i.e., more reverberance.

Generally, a banjo is not played by banging on the rim. (Even if one does, almost all the sound comes off the head anyway.) The frequencies singled out by the headless taps will be shifted when the head is firmly attached. But the implication is clear. The Bacon ring provides more places for head energy to go and dissipate without making as much sound as were it to remain with the head. The Bacon ring distributes this absorption more evenly in frequency than the all-wood rim, but there certainly will be frequencies at which the all-wood rim banjo is quieter, i.e., where the all-wood rim is, itself, more resonant.

D. Air Friction

As the head vibrates up and down, some air will flow in and out through the 1/8″ gap between the flange and the head. Flow at a surface and, especially, flow near an edge are accompanied by dissipation and possibly turbulence. The 1/8″ might be small enough that a significant part of the flow is near the edge. So this may well be a new source of dissipation associated with the Bacon ring.

This is hardly far-fetched in the context of musical instrument acoustics. Some acousticians have suggested that the narrow violin f-holes produce friction and turbulence in the in-and-out air flow which, in turn, broadens the resonances. In my own effort to simulate a belly for open back banjo research[11], a uniform rim-to-back 3/16″ gap produced a noisier spectrum than a gap with the same area but twice as wide at its maximum, tapering to zero across the rim. I interpreted that as there being relatively less dissipation in the wider region and relatively very little flow in the narrower region. On a flute, the tone hole keys come in two varieties. They can be rings with a central hole or solid disks. Flautists debate which are "better," and most players and listeners do not perceive a timbre difference. Essentially all of flute sound radiation comes from the embouchure hole, and relatively very little air actually moves through the open tone holes. Nevertheless, the difference in the sound when the tone hole is open is measurable. The solid disks, even when open, present more of obstacle to air flow and seem (from the sound) to be stirring up more high frequency noise.

In addition to being a source of dissipation, this friction would be a drag on the head motion and a substantial increase to the "air loading" known to effect drum head motion. It is the motion above the flange that is directly effected, and that region is the main source of high frequency sound. So this could be another source of the Bacon ring's general suppression of high frequencies.

The role played by the outermost region of the head is an interesting bit of the physics of how vibrating surfaces produce sound. A vibrating surface will have neighboring regions moving in opposite directions. As sound travels outward from these regions, it spreads out. The waves from the neighboring regions begin to overlap, and they tend to cancel. There is far more cancellation when the areas of the regions on the radiating surface are smaller in extent than the wavelength of the launched sound. There is typically a frequency at which the relative sizes of transverse waves in the surface and waves in the air switch. That is known as the critical frequency. For typical surface materials, sound radiation efficiency is far greater above that frequency than below.

Consider now a radiating surface of finite extent, e.g., a drum head. At a given frequency, there are patches going up and down, separated from their neighbors by the node lines. All regions are surrounded on all sides by regions moving in the opposite direction — *except* for the regions on the perimeter. They are missing outer neighbors. So the cancellation there is less complete. For the drum, this picture makes most sense for high frequency modes with many radial and circular node lines, dividing the head into many little pieces. High frequency sound, detected at a reasonable distance, comes from near the edge of the drum. And this is a region whose motion is damped somewhat by the Bacon ring.

The beginnings of this discussion are included in many acoustics texts. An inordinately sophisticated version, albeit for simpler geometries, is in ref. [15].

XII. MYSTERIES OF PSYCHOACOUSTICS

When people use "warm" to describe water, they're generally understood by others. And there are physical measures that correspond quite well to notions of warm. A "warm" sound is more problematic. It is possible for people to come to some sort of mutual understanding by sharing a variety of examples. However, it remains much harder to characterize to what "warm" corresponds in a record of pressure as a function of time. It would be very welcome if we could discuss sound more clearly than we currently do.

XIII. WHAT'S NEXT?

Fred Bacon meant this tone ring to work in conjunction with the internal resonator, e.g., as shown in FIG. 15. He gave his own description of his goal and how it worked.[1] I have suggested that the most dramatic effects of the ring without the resonator are due to the one inch horizontal flange and, perhaps, its proximity to the head. That flange may also play a crucial role in the sound of the complete internal resonator assembly by narrowing the connecting channel of the outer pot annulus to the inner cylinder. Undaunted by the meager progress presented here, I am continuing explorations into the sound of Bacon's

FIG. 15. An early Bacon Professional ff, with the nickel-plated tone ring peeking out over the wood internal resonator

entire internal resonator assembly.

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[1] http://www.google.com/patents/US823985; in the introduction to his 1905 patent application Bacon wrote (referring, of course, to the entire internal resonator assembly): *"This invention has relation to certain improvements in the construction of banjos or other similar musical instruments whereby a more lasting tone is produced and the quality of same improved. The principal objection to the banjo resides in the fact that the tones are of short duration and that they therefore have a sharp staccato quality which is objectionable. The object of this invention is to overcome this objection by providing the rim with a peculiarly-constructed annular chamber within which the partly-confined air can vibrate in harmony with the strings and cooperate therewith to produce a strong and resonant tone."*

[2] Using a DrumDial, the fundamental tap frequencies were within 1 Hz of 268 for all but the old rim with the 1/4″ brass tone ring; that one rang at 274 Hz. Note that the *perceived* pitch of a complex tone containing many Fourier components is a complex function of their relative amplitudes.

[3] I used one from Stewart-MacDonald; see www.stew-mac.com. Bill Ricard makes one, too, and also manufactures a full line of wonderful banjo hardware; see http://store.rickardbanjos.com.

[4] A felt-faced piano hammer makes contact over an extended region of head during contact. So it cannot excite head motion with wavelengths less than double that. Also, vibrational modes with nodes in the region of the strike will not be excited.

[5] Greg Deering provided the new Goodtime banjos, turning one down to fit the Bacon ring, and contributed moral support for this and related investigations.

[6] See http://sugarinthegourd.com/BaconProfessionalBanjos/ and http://www.acoustudio.dk/BD_and_Bacon_database.html or simply search on-line for newer additions to Bacon banjo history. In 1922, Bacon was joined by David Day. Day had risen from errand boy to general manager with Fairbanks & Cole, then to Fairbanks, and then to Vega. Day was a genius of design, engineering, and management. He is credited with several of the design innovations that made and still make those brands famous. With Day's arrival at Bacon Co., they became "serious" and a major player in the production of 4-string tenor banjos in the jazz age.

[7] The frequency-time resolution trade-off has long been understood mathematically. What made it a surprise in quantum mechanics, i.e., the Heisenberg uncertainty principle, was that particle motion is properly described by waves. And, more precisely, for physics to respect that uncertainty principle, the wave mechanics must be linear. Quantum mechanics is, indeed, linear, but that is an experimental question. It continues to be tested by high precision experiments. Any deviation from linearity would be a major scientific revolution. The physics of acoustics and music are always first approximated as linear systems, but this is an approximation; e.g., see ref[8]. Hearing and the associated neurobiology has fundamentally non-linear aspects. So perception is not really limited by the naive application of the uncertainty principle; e.g., see [9].

[8] D. Politzer, *String Stretching, Frequency Modulation, and Banjo Clang*, HDP: 14-02, www.its.caltech.edu/~politzer; and *Banjo timbre from string stretching and frequency mod-*

ulation, HDP: 14-03. Acta Acoustics u. w/ Acoustica **101**(1) 1, January 2015 (also at www.its.caltech.edu/~politzer)

[9] J. Oppenheim and M. Magnasco, *Human Time-Frequency Acuity Beats the Fourier Uncertainty Principle*, Phys. Rev. Lett. **110** 0444301 (2013); DOI: http://dx.doi.org/10.1103/PhysRevLett.110.044301

[10] 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

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

[12] I used the plastic fork technique at $3\frac{1}{2}''$ from the nut, described on page 20 of *Banjo Bridge Mutes*, HDP: 15-01; www.its.caltech.edu/~politzer

[13] People naturally assume that what they see and hear is what's there to be seen and heard. But that's just not true. There's always much more and often somewhat less. When those selections were recorded, I had a hard time identifying any difference. In the interim, I've acquired my first set of hearing aids. With any of the settings I now use to catch what others say without having to ask for repetitions, the difference between the recordings is like night and day. This underscores that fact that people will not all agree on what they hear or even whether two banjos sound the same or different. The quality of the perceived difference between these two recordings was a total surprise. The only connection I can make with the head taps and single string plucks is that the Bacon tone ring seems to cut the notes shorter. Note that this is not the configuration originally intended by Bacon.

[14] Location of the nodes follows from the symmetry. However, calculating the resonance frequencies, i.e., in terms of the ring cross section and elastic parameters, is impossible with paper and pencil. It's even extremely difficult to come up with a reasonable approximation.

[15] E. Skudrzyk, *Simple and Complex Vibratory Systems*, ch. 12, Pennsylvania State University Press (1968). I believe I came across this discussion in another text, too, where circular membranes were discussed. The very center can also be special in terms of incomplete cancellation and effective radiation. But I've been unable to remember where or to locate it. A heads up would be welcome.