3-D Laser Vibrometry on Legendary Old Italian Violins

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Although the violin, one of the oldest mature mechanical dynamic systems, has been the subject of scientific investigation for two centuries, a scientific "silver bullet" for quality is still elusive. The fact that two shells (top and back plates, but especially the top) are considered of prime importance for quality implies that in-plane (IP) as well as out-of-plane (OP) vibrational behaviors are important. In-plane mobilities, uniquely available from three-dimensional, scanning-laser Doppler vibrometry, were obtained for three exemplary violins from the legendary Cremonese makers Antonio Stradivari and Giuseppi Guarneri del Gesu. Combining the vibration results with acoustic scans of their far-field radiation (and CT scans for material shape and density for future solid modeling) provided a wealth of information on the vibration-radiation conversion. One Stradivari, with the highest OP/IP mobility ratio for the top, also had the highest directivity for its sound (and the highest of 17 violins examined to date).

Traditionally with tap tones, more recently with electronic excitation, the frequencies and character of resonances have been used for . . . (guidance during violin construction). It seems likely that, through neglect of their geometric properties, we have allowed a source of information to go to waste.

John Schelleng, 1968

Geometry is Destiny

Perhaps no one could better understand the importance of mode geometry than John Schelleng, whose landmark 1963 paper "The Violin as a Circuit" presented frequency scaling procedures that were needed to move two specific violin resonances upward or downward over a 3.5 octave range to create the violin octet.[1] When the pioneering modal analysis by Ken Marshall in 1985 opened up an entirely new area of violin research,[2] scientists and makers struggled to understand the significance of all the new vibrational, normal-mode information suddenly available for the entire violin over a broad frequency range, versus the few tap tones or Chladni patterns previously used just for free top and back plates. Over the last two decades, modal analysis has clarified the effect of the violin soundpost on violin mechanical and acoustical behaviors,[3] provided comparisons of modal properties of more than 100 violins,[4] and investigated the success of Schelleng's flat-plate scaling procedure.[5]

Since 2001, the combination of zero-mass-loading-force, hammer-excitation, scanning-laser response measurements with simultaneous normal-mode acoustic measurements has opened up entirely new areas, with parameters such as mode radiation efficiency and radiation damping, effective critical frequencies, and fraction-of-vibrational-energy radiated[6] being added to the various separate mechanical or acoustical parameter databases. However, all previous modal analyses had been restricted to measuring surface-normal motions. (Three-dimensional accelerometers had been available for quite some time, but mass loading is a very important problem for violins.) It was now clearly an appropriate time to apply the best modern dynamics technology in a comprehensive fashion to examine the most revered of all musical instruments, the violins of Antonio Stradivari and those of his contemporary Giuseppi Guarneri del Gesu.

The Strad 3-D Event

All of the necessary ingredients for this technology-fest came together for four days in September 2006 at the Violin Acoustics Laboratory at East Carolina University. The lab hosted an exceptional cadre of technical, scientific, craft and artistic people for an intensive examination of three of the finest old Italian violins using the most modern technologies available. The technical and scientific people included the Polytec three-dimensional (3-D) laser vibration scan team of David Oliver (author), Vikrant Palan and John Foley; author George Bissinger, director of the ECU Acoustics Laboratory, and his graduate student Danial Rowe; who added acoustic scans in an anechoic chamber; and the CT scan team, led by Dr. Claudio Sibata, from the ECU Leo Jenkins Cancer Center. Accompanying the violins and responsible for their setup and care were renowned violinmakers Sam Zygmuntowicz and Joseph Curtin (a MacArthur fellow) who each brought along one of their latest violins. The extensive preparations were aided by Fan Tao, director of string development at D'Addario Strings and co-director, along with Joseph Curtin, of the Oberlin Violin Acoustics Workshop; and Joseph Regh, vice-president of the Violin Society of America.

With only a four-day window available to complete a comprehensive set of measurements and evaluations on a group of instruments valued at $14 million, and a lot of people milling around doing various things in the Acoustics Lab (including publicity people, photographers and videographers), it was barely controlled chaos for three days. On the fourth day, after all the technology, we sat down for an extended listening session while Ara Gregorian of the ECU School of Music played the three old Italians along with the two modern violins and compared their sound and playing qualities.

Among the logistical hurdles overcome were actually getting the violin owners' permission (not trivial), proper insurance to cover eventualities (not cheap), and just getting everyone in the same place at the same time (not easy). All of the old Italian instruments were 'named' violins: the *Titian* (1715) and *Willemotte* (1734) from Stradivari; and the *Plowden* (1735) by Guarneri del Gesu. All have rich performance and ownership histories and are in good mechanical shape, the *Titian* especially, and properly set up, a crucial aspect for performers.

Measure It As We Play It

To measure the dynamics of the violin proper, it was necessary to strip it down to the bare essentials – playable if not comfortable to play – and support it in a fashion as close to 'free-free' as possible. And then excite the violin at the bridge, which is the energy 'gatekeeper' for the violin and its first major filter. Many questions have arisen over the years about the propriety of measuring the violin in a way that is so different from its normal use. We answer this fundamental question by noting with 'free-free' suspension, we measure *only* the violin, whereas when held and played we measure the violin and its support fixture. The practical difficulties in properly measuring a held violin due to support fixture (violinist) motion and boredom over the extended period of measurement are also a consideration.

Along with 'free-free' support, it was equally important to use zero-mass-loading measurement techniques given that minor mass loads at crucial places cause major acoustic effects. The excitation method of choice was a mini-force hammer striking the bridge where almost all of the string energy enters the violin, while the response transducer of choice was a scanning laser to measure surface motion.

The 'Secret'

Looming over all of this activity was the "secret of Stradivarius," a not necessarily rational reason why people are still interested in investigating instruments that have been thumped, bowed, dissembled and measured more than any other musical instrument over the intervening three centuries since their assembly. Why is it that we cannot seem to quantify the quality of their sound by scientific methods?

The Achilles heel of quality quantification may very well be that violin quality evaluations by violinists are inherently holistic, encompassing the entire mechanical (feel and playability) and acoustical (sound) universe of the violin as well as acoustical-mechanical neural feedback loops that allow a good violinist to compensate for inherently somewhat uneven response over the violin's pitch range. The complex, time-varying pressure variations (*post*-auditorium surface and reverberation properties), transduced in the hearing chain back into electrical hair-cell nerve signals, interpreted real-time by the brain into an overall sensation, are a far cry from using transducers to quantify certain motions or pressures at various places over the audible frequency spectrum, then post-processing these to create still or animation visualizations that the brain can interpret at leisure via entirely different neural pathways. Put simply, why should we expect to be able to easily see what we hear (and feel)?

Extraneous concerns such as 'investment quality,' 'brand-name,' 'controversy,' 'peer-pressure,' 'ego,' etc. that swirl about these instruments will be neglected; our criterion for great violins is simply those that great violinists own or play in preference to other readily available violins. Of course even this is not an immutable choice, since violinists have somewhat different requirements depending on whether they are performing as soloists in a large auditorium – possibly in front of a full orchestra – or playing string quartets in a small hall. For our purposes it is best just to accept violins as the tool a musician needs to create an emotional response consistent with that inherent to the music and to look at the practical requirements for such a tool.

The Fiddle Fest

While there is no question that the old Italian violins made by Antonio Stradivari and Giuseppi Guarneri del Gesu hold exalted status among the world's finest violinists, the scientific analysis of these instruments over the past two centuries has not clearly differentiated them from other good violins. Their relative scarcity, age, origin in the golden age of violinmaking by truly legendary violinmakers, along with their performance capabilities – the very best are in the very top rank – also place them among the most desirable material objects on earth. As a result, valuations in the multimillion-dollar range place them out of the reach of all but the most successful violinists; consequently, access for research can be problematic.

What is it about the best of these violins that make them so interesting musically and challenging scientifically? Our 3-D measurements in *toto* address most of the important scientific questions about these old Italian versus modern violins:

- Are their normal mode properties (frequency, total damping, modes) different?
- Do they have higher mobilities than modern violins, or is their mobility profile different?
- Do they radiate more efficiently? This is quantified by their radiativity, radiation efficiency, radiation damping and fraction-of-vibrational-energy-radiated (radiation/total damping ratio).
- Are their critical frequencies different? Critical frequency determines where the peak in the vibration-radiation conversion (radiation/total damping ratio) falls, becoming the violin's second major filter, or the 'egress.'
- Is their conglomerated internal damping (obtained by subtracting radiation damping from total damping) significantly different from modern violins?
- Are the wood density and stiffness properties different?
- Possible significance of in-plane versus out-of-plane motion (only the latter produces sound)?

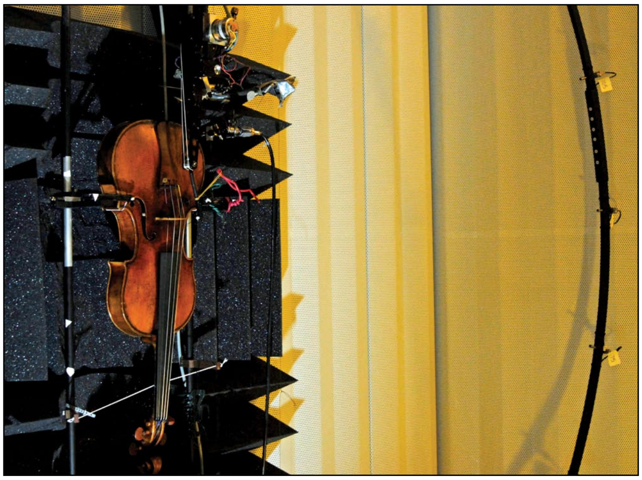

Figure 1. An old Italian violin mounted in ECU anechoic chamber for acoustic radiativity (pressure/force) measurements. Entire support fixture assembly (with force hammer tapping the violin at the bridge) was interchanged between external 3-D measurement setup and anechoic chamber. Combining rotating violin support fixture with rotating microphone array allowed acoustic scans over sphere.

Figure 2. Even three-century-old violins require critical attention to string choice, soundpost placement and bridge adjustments (the bridge is one of two major energy filters on the violin) to maintain quality. Here renowned violinmaker Sam Zygmuntowicz checks the three old Italian violins to ensure that they are at peak performance.

On Day 1, the Polytec team set up its 3-D laser scan system on a lab violin placed in a free-free violin support fixture with mounted automated force hammer (see Figures 1 and 2). To make it easy to switch between vibration and acoustic scans, the violin support fixture could easily be moved from an external frame backed with 6-inch illbruck Sonex wedges specifically built for this event into the anechoic chamber (where the 1-D scans are made) for over-a-sphere acoustic far-field measurements. The Polytec crew had precedence for the 3-D vibration measurements, the truly unique part of this experiment, since they would have to leave Wednesday afternoon. The CT scans were then performed late Wednesday afternoon after the 3-D vibration measurements. The acoustic scans, which only took a half hour for each violin, were fit in wherever feasible.

These Guys Can't Do Anything Right

Since we expected that a considerable number of photos would be taken during our measurements, the lab fluorescent lights had all been upgraded to brighten the lab as much as possible, unexpectedly providing a classic example of that subset of Murphy's Laws related to irreproducible results. The photocells that governed hammer actions were erratically triggered by the (now) excessive room

Figure 3. Danial Rowe (left), one of the official "hammer twangers," manually cocking-fires force hammer on a Stradivari violin. Sam Zygmuntowicz (red shirt) and George Bissinger adjust force hammer position.

Figure 4. Vikrant Palan of Polytec sets an alignment point to aid in splicing top, back, and rib scans into a three-dimensional model with proper orientations.

light (we did not figure this out until later), causing a superstrike that made all of us wince, denting the bridge edge, and actually pushing the bridge aside on Joseph Curtin's violin, cracking a thin veneer under one bridge foot. *Sheeesh*. This created a certain level of . . . consternation, shall we say, since the auto-hammer was essential for any measurements.

Note from George Bissinger: *This problem reminded me of my very first modal analysis experience at the training session in 1989 using Spectral Dynamics STAR software in combination with experimental measurements. My team could not get the apparatus to work properly. Chuck Van Karsen, our instructor, came over to help but to no avail. Finally Murphy got disgusted because we could not do anything right and left for another group. From then on everything worked perfectly. And so it went for us.*

Danial Rowe realized that the hammer was effectively spring-loaded and by manually pulling it back and releasing it, sufficient force was generated to create a perfect force-hammer impact. Thus began the exclusive "hammer twangers" club for those who have beat million-dollar violins with a mini-force hammer (Figure 3). This manual release then evolved into a remote string-pull arrangement, which led to the inevitable joke that "you had to pull strings to measure a Stradivarius."

Some 3-D Experimental Problems

While these were not garden-variety violins, the same support fixture and hammer-striking apparatus and procedure used for all previous violins were employed. No additional precautions were taken other than to put a piece of foam underneath the scroll end for psychological reasons when the violin was suspended as shown in Figure 4. Generally the three-laser setup on the violins ended up being quite similar to that for 12 earlier one-dimensional laser scans. There were some important differences though. Instead of a simple grid pattern overlaid on the violin, a laser time-of-flight scan over the entire violin surface prior to measurements was necessary to provide the accurate geometry required for all three laser beams to hit the same spot within <1 mm. The surface was then meshed in an irregular pattern, and certain points (*f*-hole region, for example) were excluded. The 3-D frequency range was 0-5 kHz, with three-strike averages. Good data for hammer impact measurements on violins requires use of the built-in tracking filter capability, because post-strike lateral surface motion could easily exceed many beam spot widths, possibly causing speckle dropout problems. To gather reliable FRF (frequency response function) data over three hammer strikes (not necessarily successive) in these automated scans, the Polytec quality control software (Speckle Tracking and Signal Enhancement) was essential in identifying and reducing any speckle noise.

Earlier 1-D laser scans of the violin's top plate had required excluding grid points occluded by the autohammer system, in addition to those points shielded by the neck-fingerboard and tailpiece. The 3-D scans had the same problems, but the exclusion areas were larger due to the necessity for all three laser beams to strike a common point. However, the back plate had no such limitations, and the scans of this substructure enjoyed the best coverage of any part. Scans of one rib side were also made on the *Titian* and the *Plowden* to estimate corpus radiation efficiency from the overall corpus mean-squared mobility and radiativity ratio. Time limitations precluded measurements of any other substructures.

3-D Vibration And Acoustic Results

In 1985, Marshall characterized five low-lying normal modes that contribute to the overall response in the open string region on the violin, nominally 196 to 660 Hz.[2] These have been seen for all violins tested to date regardless of quality and are now called 'signature' modes. They include the two lowest cavity modes: A0 (Helmholtz, but with compliant walls, that radiates through the *f*-holes) and A1 (first longitudinal mode with a node at the *f*-holes that creates an acoustic short there), and the three lowest corpus modes: CBR with very strong mid-region motions including the ribs but little radiation, and two first corpus bending modes labeled B1$^-$ and B1$^+$. Our 3-D measurements show clearly how important the IP component is in violin vibrations. Graphics presented for one signature mode in Figure 5 show pronounced IP motion that could be characterized as a generalized shear motion between top and back for CBR mode, while alternating anti-phase regions characterize the top and back OP motions, with the radiation from the *f*-holes also anti-phase.[7] In general only OP motions produce sound, and since the *f*-holes do not contribute, this particular mode is characterized by strong vibration and weak radiation.

All of these corpus modes except A1 have shown evidence of coupling with simple neck-fingerboard or tailpiece modes. Both cavity modes induce corpus motions reflecting their internal pressure profiles – a clear indicator of strong vibro-acoustic aspects in violin vibration. A0 radiates strongly only if a small cylinder of wood called the sound post is placed between the top and back plates just behind the treble foot of the bridge.[8] A1 does not radiate through the *f*-holes, but sometimes induced wall motion can lead to strong radiation near 450 Hz.[7] The *Plowden* had the strongest A1 peak of 17 violins measured to date, significantly broadening its response near the lower first corpus bending mode (see Figure 6). Above the open string region, wood variability starts to kick in, and the higher modes start to be less readily identifiable across violins; above ~1 kHz, statistical approaches become more feasible.

Superimposing all the vibrational and acoustic measurements in one plot made it easy to see where the corpus (top, ribs and back) or other substructure (tailpiece or neck fingerboard) was vibrating strongly, radiating strongly on average, was directional, etc. The result for previous 1-D measurements was a nine-curve 'spaghetti' plot. A complete 3-D spaghetti plot with in- and out-of-plane results would be quite complicated. However only the top, ribs (partial), and back for the *Titian* and *Plowden* were measured (the Willemotte had just the back plate and the Curtin violin just the top), so the plot shown in Figure 6 for the *Plowden* has only out-of-plane plus RMS corpus mobility curves and the averaged radiativity into the top hemisphere, making it a lot easier to read. The OP-IP comparisons appear in separate plots.

Let Me Count the Ways

A violin traditionally was expected to radiate directly via the Helmholtz-like cavity mode A0 through the *f*-holes. All remaining

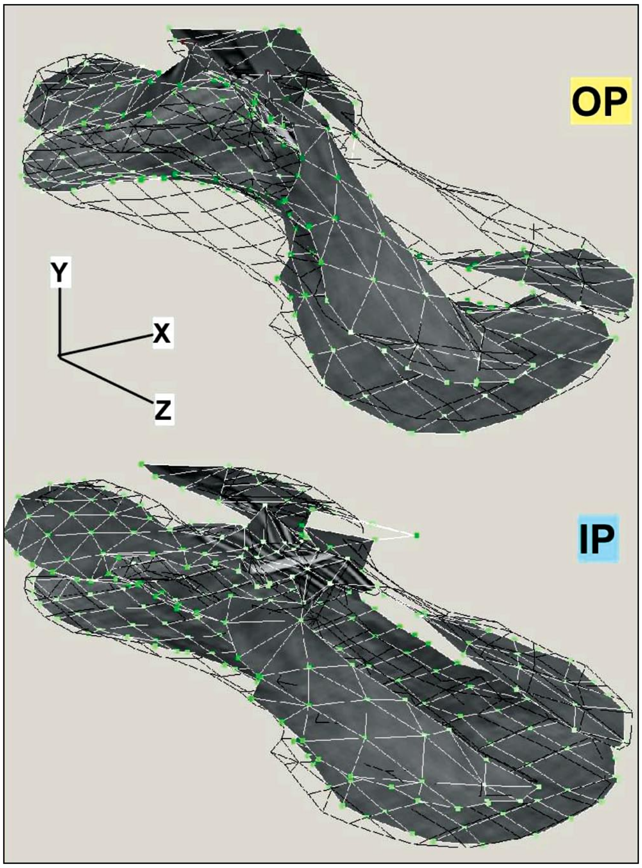

Figure 5. OP (top) and IP (bottom) motions for a strong corpus mode at 383 Hz in Plowden violin. OP motions show a ‡ nodal line structure on top and back, while the IP motions show shear-like motion between top and back (same scale for both). These corpus motions imply little net radiation.

radiation was considered to be directly from the surface. These two direct radiation mechanisms have now been joined by two indirect mechanisms. Recent experimental measurements of radiation from the violin *f*-holes, using 'patch' near-field acoustical holography in combination with the acoustic and vibration data has created a new reality.[7] The higher violin cavity modes have nodes at the *f*-holes that effectively eliminate radiation from the *f*-holes. So any radiation measured in the far field for such a cavity mode must be due to cavity-mode-induced surface motion. The *Plowden* violin shows exceptional strength for A1-related vibration and radiation, highlighting a major vibro-acoustic aspect of violin sound that had been completely neglected prior to the combined NAH-vibration-acoustic work.

And the complications do not stop there. The corpus modes can instigate significant volume flows out of the *f*-holes that for the two lowest first corpus bending modes *f*-holes actually contribute nominally half of the measured radiation in the far field. This mechanism is most important at the lower frequencies, as expected from mobility and radiation efficiency systematics. Such indirect radiation mechanisms highlight vibro-acoustic aspects of violin sound that have scarcely been examined for individual violins.

Putting It Where You Want It

Consider the practical problem facing the soloist playing a violin in front of a full orchestra. How can you avoid getting 'buried' by your accompanists, some of whom play much louder instruments than your violin? To be successful the soloist must: (1) choose a loud violin that (2) produces lots of sound in a frequency range where the orchestra does not, preferentially (3) where the ear is most sensitive, like ~3 kHz. (Good auditoriums will give the necessary bass boost.) And to be maximally effective the soloist should have a violin that projects the sound preferentially toward the audience – directional without beaming, making the maximum use of a limited amount of vibrational energy.

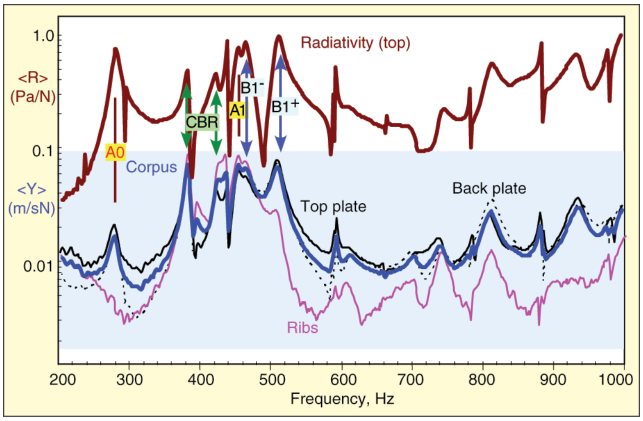

Figure 6. 'Spaghetti' diagram (partial) showing top, back and ribs and area-weighted-average corpus (top, ribs, and back) out-of-plane RMS mobilities for Plowden instrument along with RMS top hemisphere radiativity. Signature modes A0, A1, CBR, $B1^-$ and $B1^+$ are labeled. A1 (from cavity-mode-induced surface motion) radiation is exceptionally strong for this violin. Top plates are generally more active than back, while ribs are generally less active than both except in 400-500 Hz region. (Corpus mobility overall radiativity curve separation is a measure of radiation efficiency.)

Why are some violins so much more successful at being heard than others? Our 3-D mobilities offer an altogether new insight into violin sound production. Since the violin has arched plates, its vibrations will be both extensional (IP) and flexural (OP) in character. Sound waves primarily result from OP vibrations, IP being much less effective. If we compare the measured averaged mobility OP/IP ratio for top and back plates with a simple measure of sound directionality, the averaged top/back pressure (or radiativity) ratio called the directivity, a very interesting relationship appears. Our measurements show OP/IP ratios for maple backs are nominally about 3-4, decreasing slowly with frequency and very similar between the two old Italians that had top and back plates measured. Contrast this with the averaged OP/IP mobility ratio for the top plates of these two old Italians shown in Figure 7; the *Titian* Stradivari is overall significantly higher than the *Plowden* Guarneri del Gesu (which had values quite similar to a modern Curtin violin). Then compare the OP/IP ratios with the directivity (averaged top/back hemisphere pressure ratio) trends also shown in Figure 7. Again the *Titian* has the larger values and the largest overall of 17 violins of varying quality tested to date.

We conclude that if all backs have similar OP/IP ratios. their effect on directivity is similar for all the violins. Therefore, the increased OP/IP ratio for the *Titian* top should result in increased top radiation relative to the back, increasing its directivity over the others.

CT Scans and Solid Models

The last part of the puzzle of the old Italians is the material properties. Obviously no one is going to allow you to take their Stradivari to pieces so that you can test all the substructure material properties. But even in the simplest geometries. it is not a trivial matter to accurately characterize the material properties of wood. A good solid model requires accurate density, elastic moduli and shape to do even a vacuum FE calculation. CT scans provide the wealth of accurate material density and shape information that make it possible to create a 'starter' solid model with reliable position-dependent density and generic elastic moduli.

Consider the density (gray scale) and shape information available in just one slice through the bridge region of all three old Italian violins (Figure 8). The *Willemotte* Strad (top) was made in 1734 just a few years before Antonio Stradivari's death in his 90s. Compare it with the 1715 *Titian* from his so-called golden period on the bottom. Then compare both with the middle 1734 Guarneri del Gesu violin. Especially note arch heights varying about 20% – important in acoustical terms. Density values from these CT scans are consistent with the range encountered in modern wood samples.

At present, updating the starter solid model with these 3-D measurement results offers the only practical path to improve various elastic moduli values in the model without dissembling the violin.

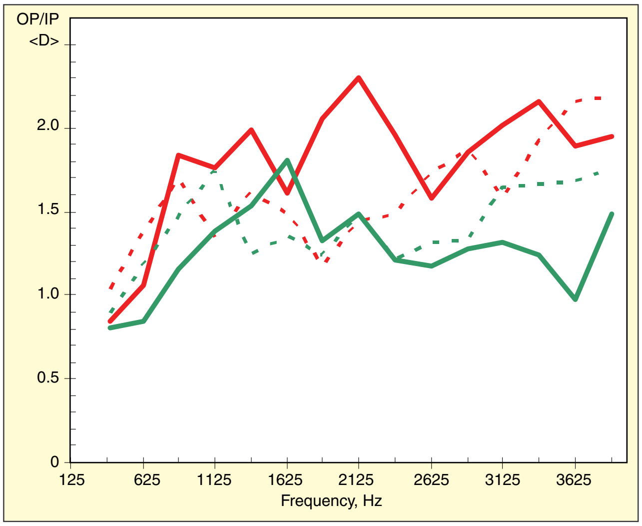

Figure 7. OP/IP mobility ratio (solid lines) and directivity <D> (broken lines) for Titian Stradivari (red) and Plowden Guarneri del Gesu (green). At low frequencies, violin sound is always close to omnidirectional.

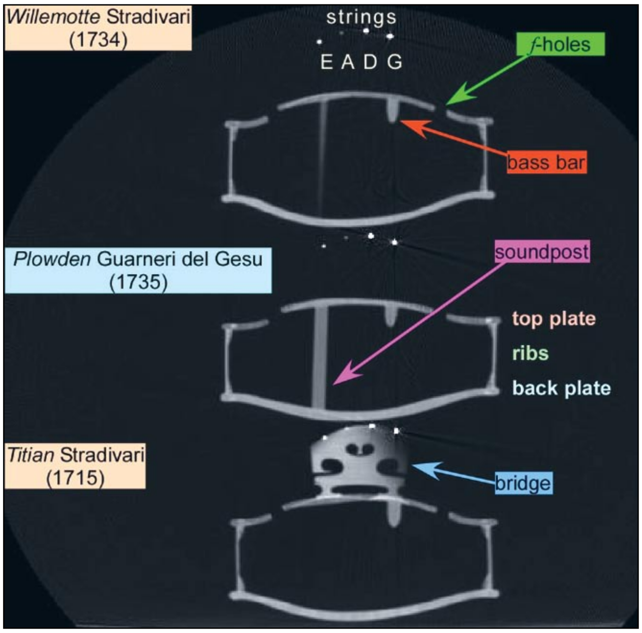

Figure 8. One annotated slice from a 1-mm-spacing CT scan of the stacked Stradivari and Guarneri del Gesu violins showing density and shape information for various substructures of each violin.

Dissembling one of these violins, in particular removing the spruce top plate – the single most important substructure – for repairs or replacement of the bassbar, offers much higher specificity, since its vibrational properties can then be measured directly. Can such updated solid models reliably predict the important vibro-acoustic interactions observed for these violins, or the observed acoustic radiation levels and profiles? This Strad 3-D data offers a wonderful opportunity to test the most competent vibro-acoustics software.

Conclusions

Besides being a lot of fun to watch the new in-plane animation results, these 3-D laser measurements have given us a whole new way to look at violin vibrations compared to the one-dimensional laser scans. The coupling of in- and out-of- plane motion for shells and the significant observed in-plane motion are important for understanding energy transmission through the violin, while out-of-plane motion leads directly to sound from the surface or from the *f*-holes at low frequencies due to corpus-mode volume changes.

A violin's overall radiation efficiency profile is suggestive of that expected for a thin-walled cylinder, implying that the primarily IP energy transmission might be analogous. Even surface-normal excitation of thin-walled cylinders leads predominantly to IP vibrations that radiate very poorly. However when IP waves reach discontinuities like the ribs or bassbar, they can be converted to OP vibrations that do radiate well.

> **. . . maybe more questions than answers, but in this era of rejuvenated experimentation on bowed string instruments, all these ways of looking at the violin offer new possibilities in understanding both what has been built and what can be built.**

Why not just make a violin with flat plates where IP motions are negligible? The obviously effective compromise reached three centuries ago resulted in arched – not flat – plates. We might wonder why? Trying not to over-simplify, ergonomics for an under-the-chin bowed string instrument are quite limiting; too big and it cannot be played, too small and it cannot be fingered well. Once the size is set, efficient vibration-sound conversion requires the lowest pitches to have wavelengths that are not too large relative to size. This leads to practical string tensions, whose force component through the bridge to the top plate tends to exceed flat-plate strengths for a nominal 3-mm thickness. Thickening the plates for strength kills the sound. Arching the plates was a practical solution, but then the IP versus OP problem reappears, of course.

Unfortunately the OP/IP ratio itself is a very complicated parameter, since it depends on arching, shape, structural discontinuities, and orthotropic elastic properties of the wood used, each individually a quite complicated matter. Look again at the bassbar in this light. Does inserting a bassbar just strengthen the top plate to combat string tension forces, a traditional viewpoint, or does it also provide an essential discontinuity that appreciably increases the OP/IP ratio, enhancing sound production and directivity?

Finally we go back to the first link in the energy chain from string to corpus to sound. The violin bridge is the single most important filter in a properly made violin. This prominence has been ascribed to *bridge* in-plane vibrations driving surface-normal top plate motion. However strong top-plate, in-plane motions observed at the bridge feet lead to the question: can the bridge drive this top-plate motion directly? Or do the bridge feet just follow top-plate IP motion that originates from surface-normal excitation of plate vibrations and the subsequent coupling between OP and IP motions in shells?

Again, maybe more questions than answers, but in this era of rejuvenated experimentation on bowed string instruments, all these ways of looking at the violin offer new possibilities in understanding both what has been built and what can be built. And there's also a lot of fun (including balsa wood violins) in the doing.

We would like to thank all the participants who contributed mightily to the Strad 3-D event and to acknowledge the owners of the Stradivari and Guarneri del Gesu violins who graciously allowed us to measure them, as well as the support of the Violin Society of America, which also provided funds to cover instrument insurance costs.

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