A Panel Presentation: The *Strad*3D Project

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Marilyn Wallin: Welcome to the last presentation of this 2007 VSA convention! It is going to be wonderful, and I'm going to let Fan tell you what it's all about. My thanks to Fan for everything he has done with this project and with this convention. I hope everyone enjoys this.

INTRODUCTION TO THE STUDY

Fan-Chia Tao: Thank you, Marilyn. Well, this has been a long and interesting project. Its genesis was at the VSA Acoustics Workshop at Oberlin College, so I thought I would take a few minutes to describe some of the activities at the workshop and how it started.

For many years several key members of the Catgut Acoustical Society—which was an organization of people very interested in violin acoustics—and members of the Violin Society harbored plans for holding acoustics workshops for violinmakers and violin acoustics researchers. One of the key visionary members was Joe Regh, VSA vice president. He persuaded the boards of the Catgut Acoustical Society and the VSA to sponsor an acoustics workshop at Oberlin College, where the existing violin-making and bow-making workshops were already in existence. So in 2001 the two organizations asked me to organize an acoustics workshop. One of the first things I did was to call up Joseph Curtin and ask him to help me organize such a workshop. Fortunately, he said yes.

For the first workshop we had about 18 participants, and each succeeding year the workshop expanded. Sam Zygmuntowicz joined us in the third year and added a new perspective and a huge jolt of energy and ideas. He helped propel the workshop to a different and expanded level.

One of the integral members of the Acoustics Workshop from the very beginning has been George Bissinger, who is a professor of physics at East Carolina University in Greenville, North Carolina. He had assembled one of the world's most advanced acoustics laboratories for measuring violins. We asked him which violins he had measured and he showed us all sorts of interesting graphs and qualitative evaluations of violins in trying to relate to all these violin parameters. It was fascinating, but we discovered that he had not yet had the opportunity to measure a really fine Old Italian instrument. Sam suggested that this could be a fabulous opportunity to do so. So we all looked at Sam and asked, "Can you get us one?" That is kind of how the project started. We talked about it for several years and finally it came to fruition last summer and fall. A key component was the support of the VSA and the CAS Forum, because they gave us funding for the liability insurance and to help pay for some other expenses.

The goal of the VSA Acoustics Workshop is to bring together the leading violinmakers and violin acoustics researchers. Every summer we have a program for about a week of talks, lectures, demonstrations, and projects that are fairly informal. The hope has been that through this exchange of information future projects would spawn. Historically, the violin-making and the violin acoustics research communities have always kept to themselves. Also, violinmakers have approached or treated violin acoustics with indifference, at best, and even hostility in some cases.

That attitude is rapidly changing. An example of that was the merger of the Catgut Acoustical Society with the VSA several years ago. That has really brought violin acoustics into the mainstream, and today I see almost no hostility amongst violinmakers towards violin acoustics or science. There's still a lot of indifference or, as Sam will say, puzzlement as to what the usefulness of violin acoustics to violin making is, which is a valid question. It's a conundrum. Sam will attempt to answer that question later in this presentation.

The group of Catgut Acoustical Society members that had a fairly significant overlap with the VSA has continued to do projects under the CAS Forum banner within the VSA. Some of the projects that we sponsor are the Acoustics Workshop every summer at Oberlin College, special programs at the VSA conventions, and also projects like this *Strad*3D project. We have many other projects that are in the works, so we hope you will support them.

Now, I invite Joseph Regh to tell us about the role of the VSA in this project.

Joseph Regh: Coming from a scientific background myself, and having my brain shaped at a very early age in life to look at things from an analytic and critical point of view, this is a culmination of one of my wildest dreams: to apply advanced science to our antique musical instruments. When I first got involved in the idea, I was absolutely thrilled and filled with probably what turns out to be unrealistic expectations and hopes, because the violin is a much more complicated system than we can imagine. Looking at it seems to change the sound. If you look at it pleasantly, it may change one way, and if you look at it harshly, it changes in another direction.

I was very much in favor of having this project go forward. Having been involved in both the VSA Board of Directors as well as the CAS Forum, I did my utmost to try to get the project off the ground and to have the VSA and CAS provide funding to make this project feasible.

One of the most incredible things that I learned, aside from all the science, happened during the final playing of the instruments. Not only did we play three famous Cremonese instruments, but we also played two contemporary instruments, one made in 2006 and the other in 2005. We had a professional concert artist play all five instruments. It takes about half an hour before your ear gets trained to a level that you can close your eyes and when you hear an instrument, recognize which one it is. I'm very happy to report that the level of the craftsmanship and performance that those two contemporary makers have achieved rivals that of the old Cremonese. It was an incredible experience to hear the *Plowden* Guarneri *del Gesù* and one of these two contemporary violins played one after the other, and I couldn't tell the difference. As you will see when you see the pictures and the reports, this is a big step in the history of the violin industry.

Sam Zygmuntowicz: I feel a little out of my depth to have been involved in the project at all. I characterize myself as a curious violinmaker, as opposed to a scientist or a technically trained person. Nevertheless, after Norman Pickering introduced me to the world of violin acoustics, I've gone down the "rabbit hole," so to speak, and have gotten very deeply into this. Due to the VSA Acoustics Workshops I think some very interesting things have happened that have changed the direction of violin making and influenced the world of scientific research too. Our goals are converging. I'm quite excited to be able to show some of the results that we have here which are going to be available to all of you. This is an unprecedented amount of information that's going to be available to laymen.

This is the *Strad*3D DVD and today is the official release date.* Tom King and Fan Tao did an all-nighter on this (maybe several all-nighters) to get it together. It is essentially an outgrowth of Dr. George Bissinger's research. My role was, essentially, the Strad wrangler, but I've also meddled in it a bit. What struck me about the research is that it gave a unique window on the violin, one that was not at all exclusive of our

*An expanded and updated 2-DVD version of *Strad3D* was published in 2009 by Samuel Zygmuntowicz and George Bissinger. See <www.strad3d.org>.

usual way to look at it. I think all of us have sheaves of measurements of any instrument that we can get our hands on, and there are many expensive books like the Guarneri book published by Peter Biddulph. Such archival information now has become widely available, and I think access to that kind of information is largely responsible for the increased level of contemporary violin making as well. I don't belittle that kind of study at all, but it goes up to the point of studying a fixed static object as if it were an artifact, as opposed to something that is defined by what it does. This acoustics research, and modal analysis in particular, gives you the opportunity to see not only what a great violin looks like, but also how it functions. This project attempted to look at the instrument from three dimensions. It's not 3-D just because of 3-D cameras, but because we're looking at it from every possible point of view. I'm going to take you on a tour of the disks so you can see what's on them.

Mr. Tao: I want to mention that the *Strad*3D DVD can be purchased now for $75. All of the proceeds will benefit the CAS Forum and violin acoustics projects at the VSA Acoustics Workshop.

Mr. Zygmuntowicz: One of the obvious questions is what is this disk, what's on it? The harder question to answer is how one will use it and learn? At the end of this afternoon, hopefully we'll be able to answer the question of what violinmakers can learn from this.

The violins that we were able to get for these studies are some of my all-time favorite instruments: two violins by Antonio Stradivari, known as the *Titian* (1715) and the *Willemotte* (1734), and one violin by Giuseppe Guarneri *del Gesù* known as the *Plowden* (1735), my favorite (Fig. 1). Some of my clients were very generous in lending them to us.

The DVD contains high-quality photographs of these instruments, both the standard

Figure 1. The Strad3D Project included measurements of three Old Italian violins. Pictured from left to right are the Plowden *made by Giuseppe Guarneri* del Gesù, *Cremona, 1735; the* Willemotte *made by Antonio Stradivari in Cremona, 1734; and the* Titian *made by Stradivari in 1715.*

instrument archival photos and more intimate shots, including details that makers enjoy from a craftsmanship point of view. To form a 3-D picture of the violins, you need to see them from both familiar ways and in new ways.

More casual photos were also taken at the testing session in North Carolina, and they include some very nice detail as well. I'm partial to the shots that have lots of reflections on them, because I think you actually see the violin even better than you do in the flat catalog photography.

We've included standard specification sheets from my archives, and there are graduation charts from which Jeff Loen made contour maps of the three great Italian violins. Then we get into the things that no other books have yet, such as CT scans (the popular acronym for x-ray computed tomography). The CT scans were performed for us by Dr. Claudio Sibata at the Leo Jenkins Cancer Center at East Carolina University. Shown here is a "Cremona sandwich" (a three-violin stack) going through the CT scan tunnel (Fig. 2). By the way, that's $14M of violins passing through this x-ray machine, as it was more economical to measure them all at once.

The CT images were large. Afterwards, John Waddle and Steve Sirr, who've also done a lot of work with CT scans of instruments, turned them into little movies. This is like an incredible voyage with unexpected views of familiar objects. I've started with the most familiar and we're moving towards less familiar ways of seeing these instruments. From these you can get all the arching templates you want. These are quite accurate, fairly high-resolution images, and fascinating to watch. I think it gives all of us who try to make these things a much different feeling for how the curves flow together and the transitions between the arching and the graduation and the edgework (Fig. 3).

There are multiple views in these CT scans

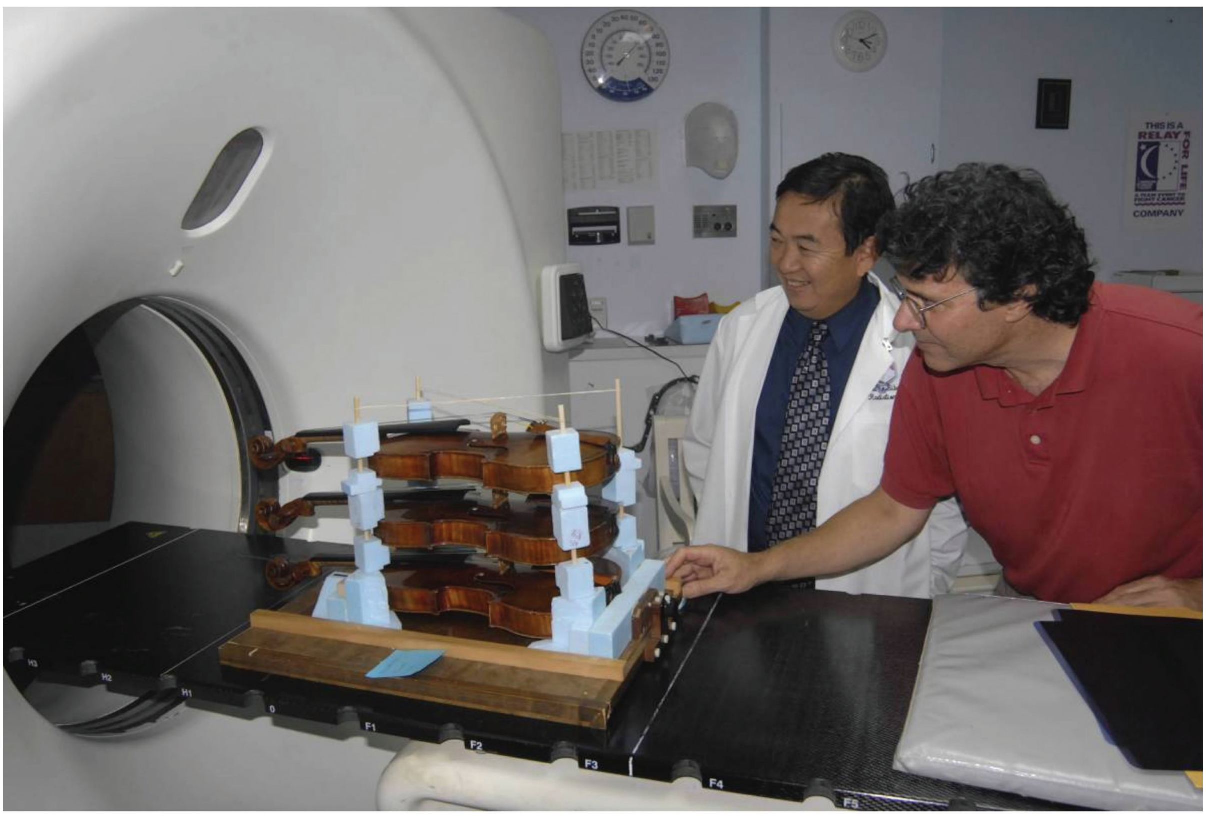


Figure 2. With the Old Italian violins stacked three high ("Cremona sandwich"), Dr. Claudio Sibata, head of the medical physics staff of the Leo Jenkins Cancer Center (East Carolina University), performed the x-ray CT scans. Sam Zygmuntowicz is shown assisting.

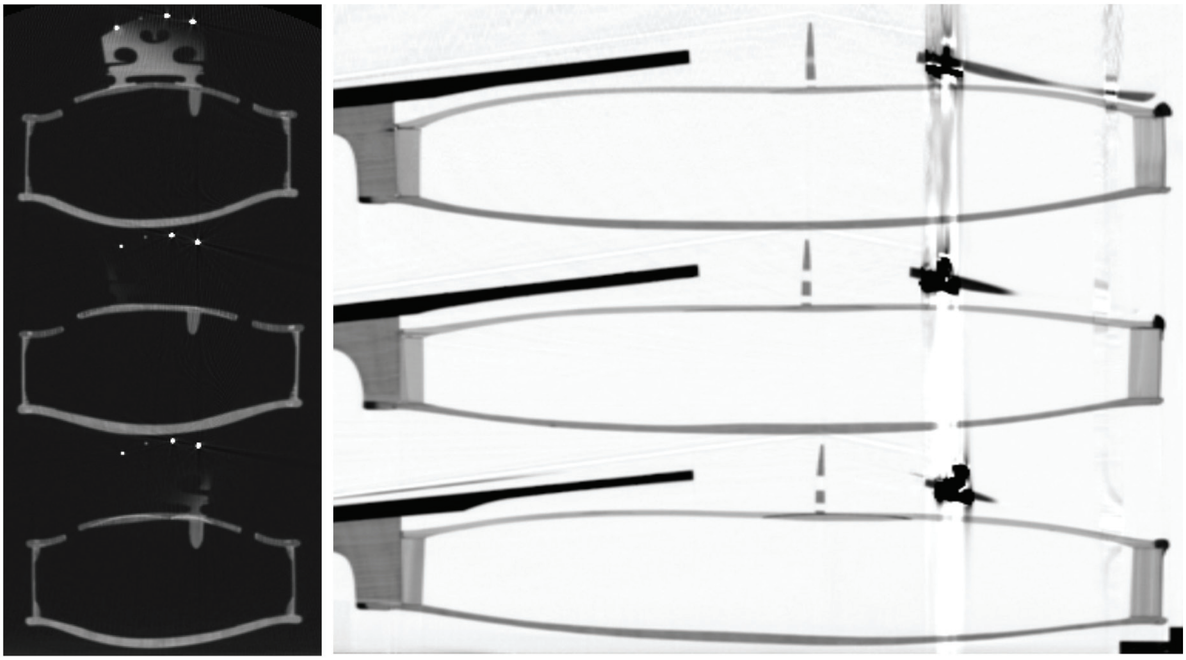


Figure 3. CT cross-sectional measurements of the plate and rib thicknesses for end view (in the bridge plane in C-bouts) and side view (slightly right of the center plane) of the three stacked Old Italian violins. Top to bottom are the Willemotte *Stradivari (1734), the* Plowden *Guarneri* del Gesù *(1735), and the* Titian *Stradivari (1715). The brightness scale reads directly in density with proper software. (See Figs. 34-36 for CT density profiles extracted from these CT scans.)*

including snapshots of cross-sectional views along the lengths. This is telling you not only about the shapes, but also the densities of the material. And you can see where the purfling is set in. If you get in closer, you can see the grain lines of the spruce (Fig. 4).

There's an incredible amount of information just from purely a making point of view. And there are the outlines of the three Old Italian violins, which I suppose could be happily blown up and used to make nice violins (Fig. 5).

Besides the CT scans, there's other very cool stuff in the DVD. This is getting us closer to the question that I think all of us have as we work: What is this object that we're trying to build and how does it work? With each level of this documentation, we go a little deeper into what the real essence of the violin is, which brings us to the 3-D work.

What I'm showing you here are all the things that are on the disk that you're able to buy now. I'm still finding my way around it, but all these data are on that disk, which is an amazing thing.

Part of what I've talked about is how an acoustical functional vision of the violin is different than the usual way that we think of it as makers. One of the first things people talk about—Joseph Curtin has been very involved in this—is testing the spectral response of instruments. Every instrument has a very distinctive resonance profile: where it vibrates well and where it doesn't. When you play a note, it is made up of a whole series of vibrations, the fundamental and the harmonics. It's like shooting a shotgun through a sieve. Wherever the little pellets happen to find an opening, that's where something comes out. The shape of that sieve is what's going to determine the sound. One of the first ways to approach that is what's called making a spectral analysis.

The radiation data for some of these instruments are in this DVD, as well as a trial version of Spectra Plus™, which is a nifty spectral analysis program. If you get these things and want to experiment with playing with the raw files, they are there. I've also included the spectral output of each of these violins. This one is for the *Plowden* (Fig. 6). There's the first air peak, there's mode

Figure 4. CT measured images of the spruce tops of the three Old Italian violins. Left to right are the Titian *Stradivari (1715), the* Willemotte *Stradivari (1734), and the* Plowden *Guarneri* del Gesù *(1735). (See Figs. 34-36 for CT density profiles extracted from these CT scans.)*

Figure 5. CT images of the rib outlines of the three Old Italian violins. Left to right are the Titian *Stradivari (1715), the* Willemotte *Stradivari (1734), and the* Plowden *Guarneri* del Gesù *(1735).*

B1⁻, as some people call it, and B1⁺, which would be about where the wolf note would be.

It is very interesting to compare the spectra for the different violins. The red curve is for the *Titian* Stradivari, which is a brilliant, strong, and almost strident concert violin of the first rank (Fig. 7). The *Plowden* Guarneri is probably one of the most seductively pleasant and enjoyable mellow fiddles you could ever play. You can begin to see that just by flashing these back and forth. At low frequencies, those big peaks are quite a bit higher on the *Plowden*. At high frequencies, up around 3,000 Hz, the *Titian* is stronger, which is a very good way to begin to see a different picture of sound. We also have the spectra for our three master Italian violins (the *Titian*, the *Willemotte*, and the *Plowden*) all superimposed (Fig. 8).

One of the ways to use this is to observe the peak there, and ask how is the violin actually producing that sound? The next step is to find out how the violin produces that sound. To utterly simplify a complex subject, when you play a violin, you're basically giving it a shove, and it tries to return to rest by dissipating its energy at all the little places that it can. There's a lot more to say about it. We could just leave this scan for the *Titian* up here and take a look at some of those peaks. Let's see what this B1⁺ peak, the wolf note at ~540 Hz, is.

This was the testing scene in September 2006 in George Bissinger's laboratory at East Carolina University, with a lot of very smart guys trying to figure out whether the equipment was working (Fig. 9). We were assisted by a team from the Polytec Corporation that brought and operated one of its advanced 3-D scanning laser systems. George has been working with lasers for a very long time, which have given amazing animations and a great deal of information that he'll show later. This, I think, was the first time this type of laser diagnostic equipment had been used on violins. As you can see, there are three "cameras"—I'll call them cameras, but they're not cameras—that each shine a single laser beam at the same point on the violin.

When an impulse was applied to the violin by a calibrated hammer, the three laser beams measured the motion of the surfaces of that violin as they went in and out, back and forth, and up and down. The Polytec software was able to instantaneously process that into animations for any single frequency of motion. For each violin, measurements were made at a large array of points on their surfaces like that on the video monitor shown here (Fig. 10).

When the lasers were turned on, you could see something that you normally can't see. This is what I call the invisible violin. This is the violin that's actually doing all the "violining." Looking at all that motion, there are all kinds of questions that violinmakers might ask.

The Polytec ScanViewer software they supplied for public use allows you to view the files that they prepared. The viewer is included on the disk, along with the files that you can view. Everything that I'm showing you today is on that DVD. Also, the help files with the software are actually pretty good. With a little fooling around, it's quite easy to use. I've been doing it for a little while.

This is Dr. Bissinger's automated hammer, which became less automated shortly after we got there (Fig. 11). There was a highly calibrated solenoid that was designed to precisely tap the violin bridge. However, it malfunctioned for a reason not understood until some time later. Never at a loss, Dr. Bissinger attached a rubber band to it and a little voltage meter and we all took turns pulling that little hammer back. With four strikes per point, 600 points per instrument, and five instruments, we all got repetitive stress injuries, and so we're now known as the "Hammer-Twangers Club." That's just a little bit of what the scene was like.

The real long-term value of this research is going to come from a lot of hard number crunching by Dr. Bissinger and his associates. These data were taken in a prescribed, calibrated manner, and Dr. Bissinger has already been extracting damping numbers for all the modes, radiation efficiencies, and other things that he will speak about. The results can be appreciated on many levels.

As makers, we have an object—the violin—and we're trying to make it work in a certain way. What we do to that object influences how it moves. If its plates are more curved, then it's stiffer. If they're thicker, it's stiffer and heavier. All those things directly affect the violin shape, and the shape directly affects the frequencies at which it will vibrate, producing sound in the air.

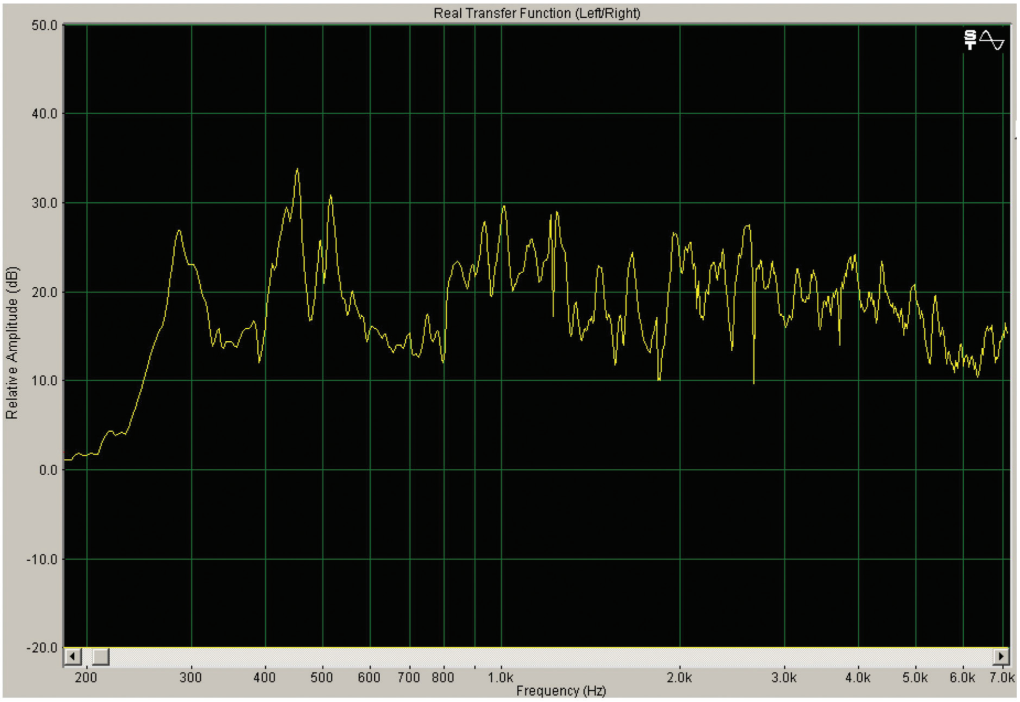


Figure 6. Sound spectrum radiated from the Plowden *Guarneri* del Gesù *violin. Amplitude units are in dB. An impact hammer tapped the bass corner of the bridge, and the microphone was positioned 37 cm from the violin's central axis.*

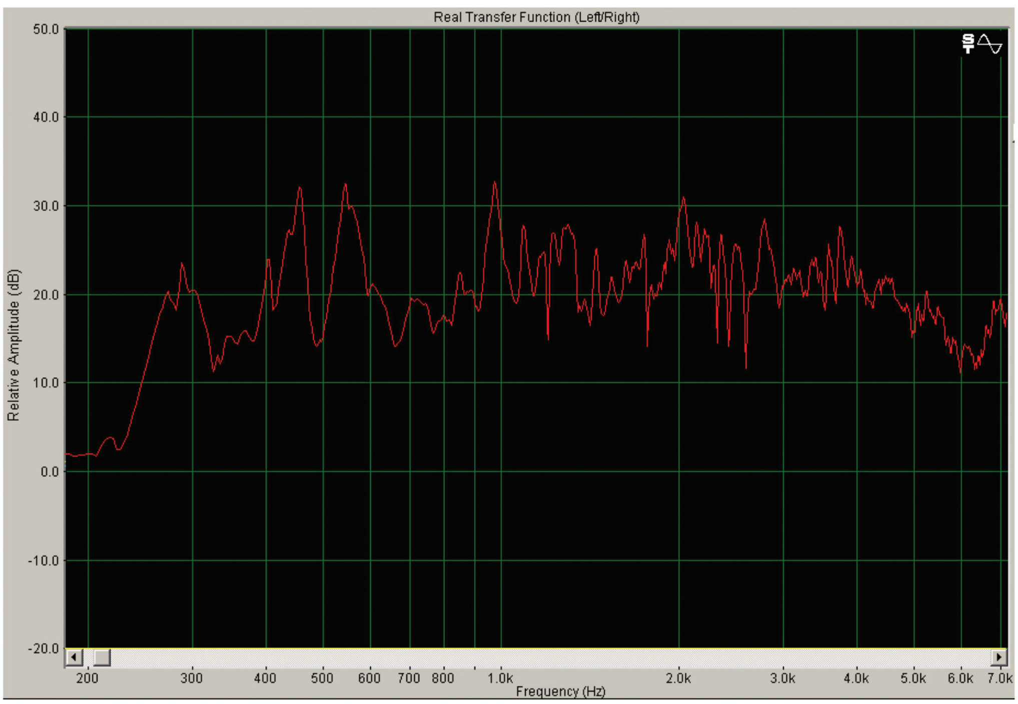


Figure 7. Sound spectrum radiated from the Titian *Stradivari violin. The test configuration was the same as in Fig. 6.*

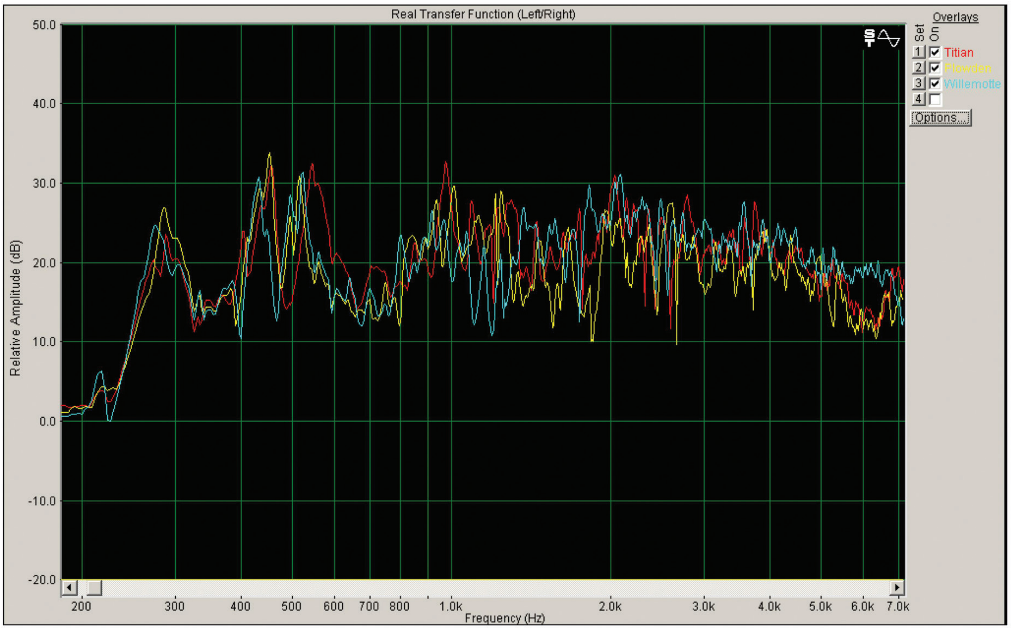


Figure 8. Sound spectra radiated from the Plowden *Guarneri* del Gesù *(yellow), the Titian (red), and* Willemotte *(blue) Stradivari violins. The three overlapping spectra can be distinguished by the color code. Test configuration was the same as in Fig. 6.*

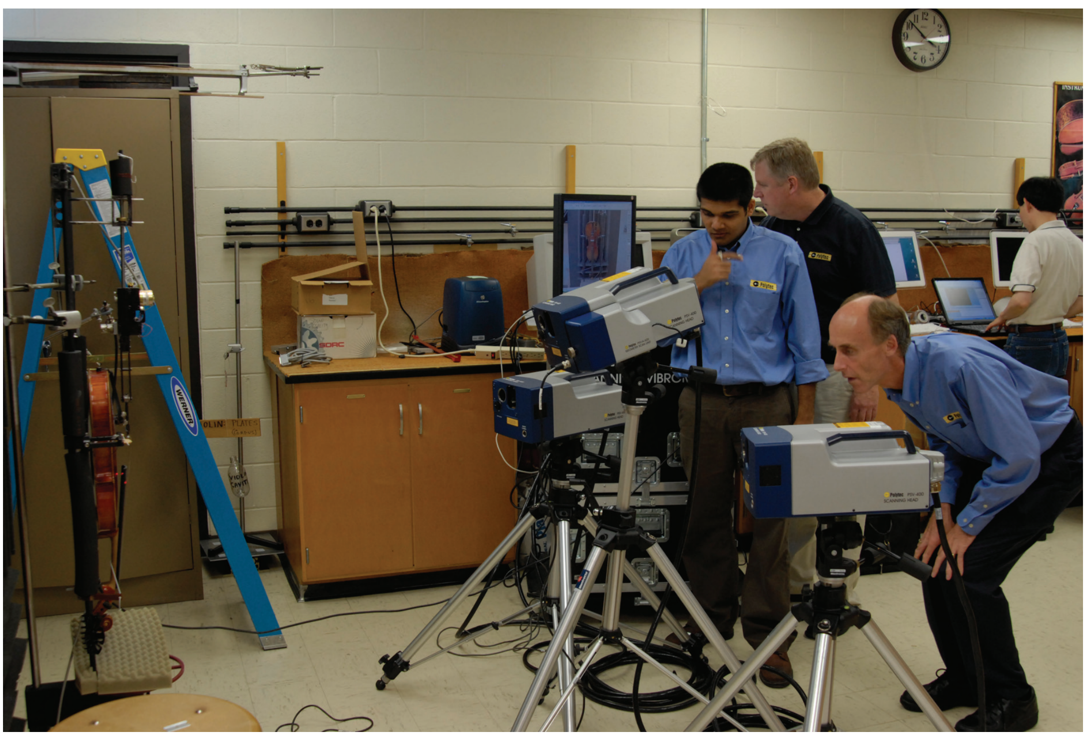


Figure 9. Strad3D Project activity in George Bissinger's acoustics laboratory at East Carolina University in September 2006. The Polytec team of (front to back) David Oliver, Vikrant Palan, and John Foley set up the three lasers required for three-dimensional vibration scans.

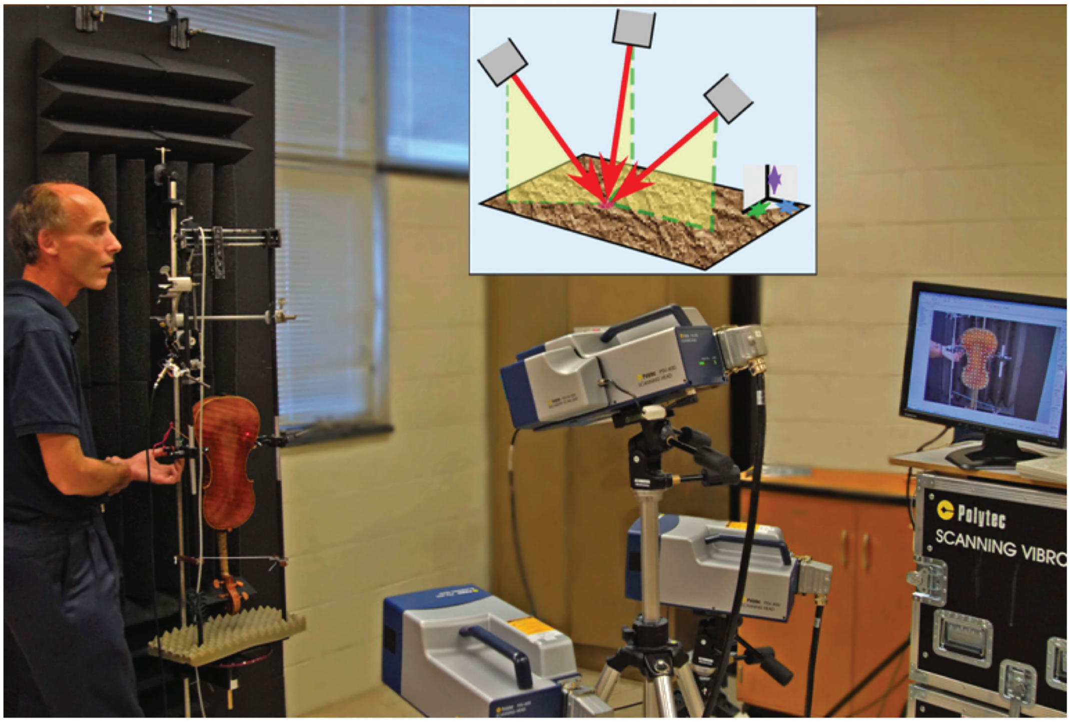


Figure 10. The Polytec Scanning Vibrometer using three lasers was used to make 3-D vibration scans of four violins. David Oliver of Polytec, Inc. is shown conducting mobility measurements of the back of the Plowden *Guarneri* del Gesù. *The array of multiple test spots is visible on the video monitor.*

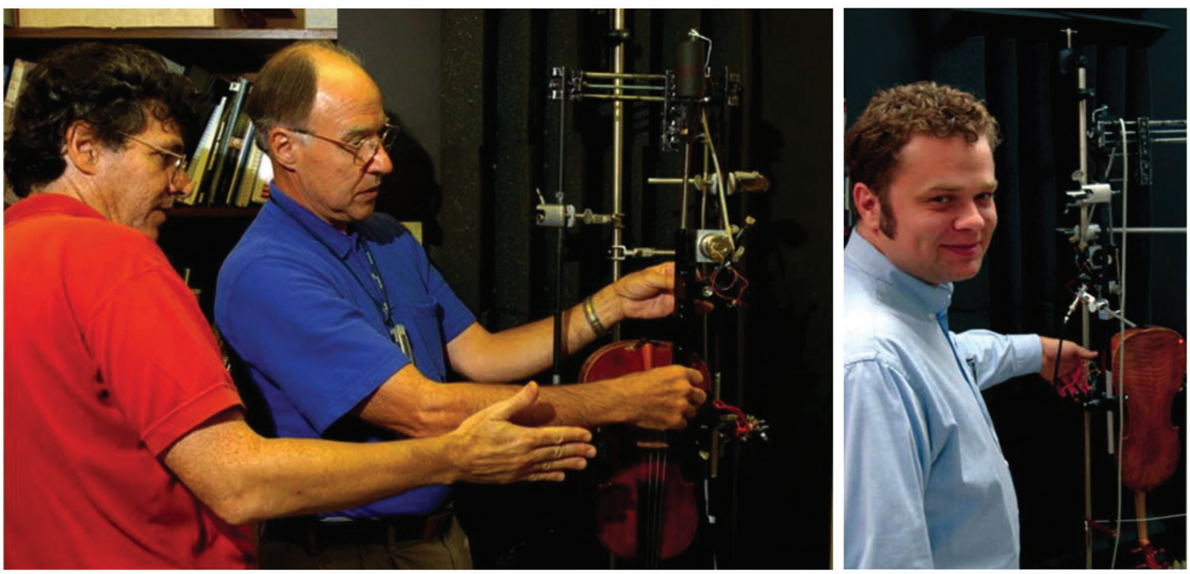


Figure 11. Sam Zygmuntowicz (red shirt) and George Bissinger adjust the impact hammer position, and Danial Rowe (right), one of the official "hammer twangers," manually cocks and fires the impact hammer on the side of the bridge of a Stradivari violin.

So if you influence the way it vibrates, you influence the sound. Everything else about the way it looks is window dressing.

There's the violin up in the rack. And right now, this is at 273 Hz, the frequency for this violin which acoustics people call the A0 mode, the main air volume resonance. Whatever vibration there is on the surface is caused not so much by vibration of the wood, but by vibration of the air underneath it, which is then in turn moving the wood and putting forth quite a bit of sound. We can look at this in basically in what you'd call 2-D, but it gets more interesting when you turn it into 3-D. This is an extremely sophisticated, never-before-seen image. In other ways it's quite crude compared to a normal photograph of a violin, but it contains information that no photograph ever would.

I played a game once with a group of violinmakers, asking them, "What do you know about any given feature on the violin that you've proven to yourself to your own satisfaction, that you just didn't learn from someone?" Everyone in the room was silent, including me. It's remarkable that people who are as skilled and trained as we are as a group, how little we know about what is going on. What we basically know is that if you do it very much like the people in the past who've done very well, you'll do something pretty good. This, for me, is an existentially unsatisfying place to be in.

This kind of information gives us the opportunity to move past that very static reproductive way of thinking to actually answering questions. For instance, what does a soundpost do? That's a question people always ask when I show them this stuff. They see me spending a lot of time trying to get the computer to work and then ask, "What do you learn from this?" and "Are you using this in your work?" I find those very difficult questions to answer. However, if they look over my shoulder for more than a few minutes, they find it interesting that the soundpost isn't moving, but everything else is moving around it. So it's not what you learn, it's what you see that you couldn't see before. What will you learn from what you can now see? At the end of this afternoon, after you hear Dr. Bissinger speak, and especially if you take home this DVD and spend a lot of time looking at it, you will never see the violin in the same way.

Editor's note: For the remainder of Mr. Zygmuntowicz's presentation, he commented on the video images of computer-simulated violin motion shown on a screen to the audience, and which are included in the Strad3D DVD.

I like to look at what's coming out of the instrument, which we have a picture of here. That was at ~3xx Hz. It could be that little peak down here, which for vibration that's generating sound out of the violin, is a very low peak. In this animation the violin is moving like crazy, which shows that a vibrating violin does not necessarily produce a significant amount of sound. It's sort of moving almost symmetrically, so it's pumping in as much as it's pulling out.

However, the $B1^-$ mode peak at 471 Hz is generating a large amount of sound, and probably for no more motion (Fig. 12). Going back to the view of it, this symbol allows you to move the violin. It is quite remarkable how it's not just plate tuning by tapping the tops and the backs. When you look at a how a violin moves, all of its parts move together in ways that you might not imagine.

If you move into the main wolf-tone mode, the $B1^+$ mode as it is called, notice that the soundpost is still not moving. The soundpost is for the lower modes. It holds the violin still while letting the whole world oscillate around it. This is a picture of the movement of this violin slowed down a zillion times and magnified a zillion times. As soon as they took the scan, these pictures could appear on the screen. They didn't have to process it. This is literally what the fiddle was doing, and more.

As we start to go up in frequency, initially the soundpost remains motionless, but then it becomes increasingly active at higher frequency values. And now things are going both ways. Then it's moving more on the soundpost side, and those little *f*-hole wings are going nuts. You can change it. This has a lot of different ways to look at things. Some of them are much clearer than others. This is very exaggerated, but it shows you vividly what's happening. There's a lot coming out of the back here, and that little wing of the *f*-hole is going and the soundpost is starting to move more. And then the bassbar side is not moving, but the soundpost is moving quite a lot.

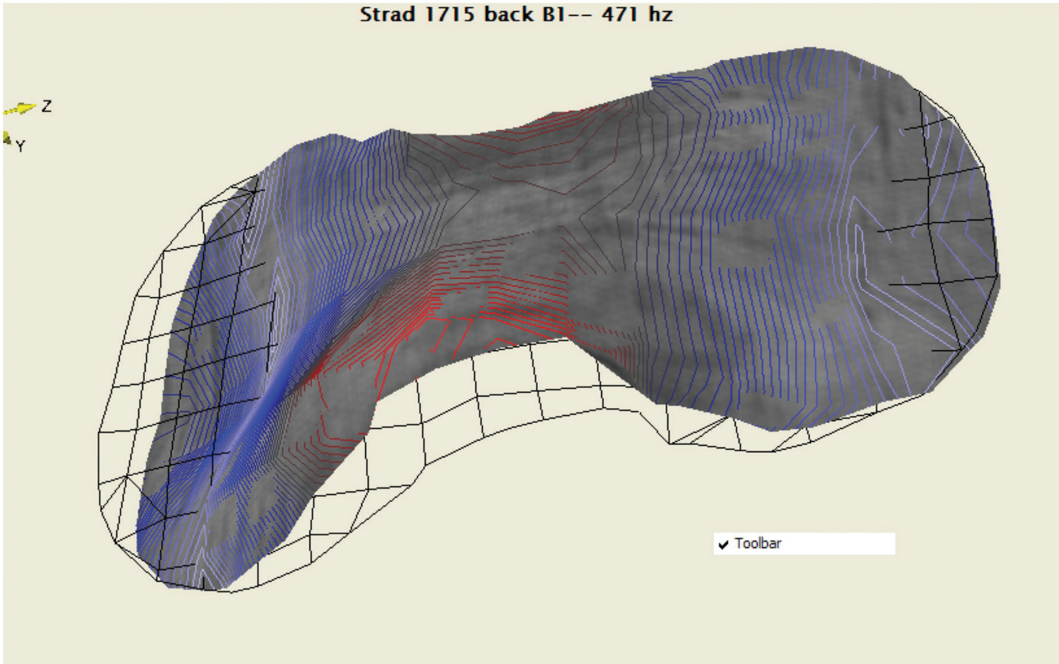


Figure 12. A freeze-frame image from a video presentation of the computer simulation of the B1$^-$ mode motion at 471 Hz of the back of the Titian *Stradivari violin.*

What does the bassbar do? I don't know if I'm quoting Norman or not, but someone said that the mass of the bassbar is very important for giving the bridge foot something solid to push against at high frequencies. Maybe it should be called the treble bar rather than the bassbar. This kind of picture shows that that might be the case, that at high frequencies the bass side of the fiddle moves much less.

These kinds of speculations become very easy to make once you have the pictures in front of you. What do you see and what does it look like? I think this research will have some universal significance for quite a long time to come. As individuals, we can look at these things and draw our own conclusions.

At lower frequencies the violin vibrates in ways that you can imagine, but at high frequencies, it starts doing things that you just wouldn't believe wood could do. There are little inferences that come very intuitively. I showed this to Cho-Liang Lin, the violinist who plays the *Titian* Stradivari and who was very generous in helping us get the loan of it. This is in the nasal region of the fiddle. They say that's exactly where you put your shoulder down, that must be damping that area. Well, one can ask if that is good or what? Is there more activity in the nasal region on the back and is it useful for the shoulder to be touching the instrument? Maybe it's not such a bad thing. These are the kind of questions you can ask and come up with working hypotheses. Also, if you want to try to affect a fiddle, this gives you hints of where you might make it thinner or leave it thicker.

There's a lot of radiation at some of these higher frequencies, for example, at 1705 Hz. Most of us think in terms of musical notes, so 1705 Hz doesn't mean much. So we included a spreadsheet in the DVD that has equivalencies of musical notes to frequency numbers. To make the translation, you can pull that up and see that 1700 Hz is roughly somewhere between G-sharp and A.

It's remarkable that the motion of the little *f*-hole tabs produces a lot of sound. *[Shown in the video of computer-simulated violin motion.]* This leads to another question regarding the corners. A lot of people try to make guitar-shaped models, because it's not obvious what purpose the corners serve. The corners appear to be just little do-dads and it would be a much more modernistic design to just cut them off and make a guitar-shaped violin. It's been tried many times. Why doesn't that work so well, or what do the corners do? Well, this actually can start to tell you. If you look at this point right here, it's not moving hardly at all. But if you look at this point on the C-bout inside the corner block, it's moving like crazy. So the corner block is providing a stiff seesaw around which the top plate is pivoting and squeezing that rib. As it's squeezing that rib, the back isn't moving very much, but the top is. What's happening to the rib? It's got to be bulging out as it's being pushed down. So, quite a lot of sound must come out of the ribs. You can find this with your bare fingers, but here you can actually see it and analyze it in a different way.

This was taken at great effort and taught us remarkably little, but I just have to show it. This is a close-up. *[Shown in the video of computer-simulated violin motion.]* There is quite a lot of activity around the central area of the violin top, which was one of Oliver Rodgers's main messages. One of his early experiments, which preceded my "Gluey" experiment, was the thin-strip project with Pam Anderson, where he glued little reinforcements to the top of the violin and found that that area was extremely sensitive.

The laser is still relatively new technology and I wanted to see what this could do. So we loaded one area with as much detail as possible, for consideration at a future time. It might be possible at some time to do this project with this much and more detail all over the body and create a full three-dimensional quivering model. That will have to wait, but we do have a sample of it.

One thing that I find very satisfying is just how natural the motion of the violin is. It looks like a stingray or a bird. Manmade design, at its best, mimics natural design, which has been worked out in nature's wind tunnel for several million years. We are creating something that's supposed to work harmoniously. And then it gets quite interesting as you get to the super-high frequencies.

This is something that I think that no one has seen. *[Shown in the video of computer-simulated violin motion.]* We took a couple pictures of ribs, which have not been studied too much. Stimulated by this project, Dr. Bissinger has gotten quite involved in the study of the ribs, which he can tell you more about. Just in case you thought the rib structure of a violin was stationary, with the back and the ribs being like a box, they're not, which is the moral of the story here. This is the bass side, the G-string side of the *Titian* Stradivari. It's moving all over the place. Oliver Rodgers talked quite a bit about how the radiation from the violin at some of the super-high frequencies, difficult to track with this kind of analysis, is very directional. You'll sometimes find a spot the size of a dime on a rib that radiates a little beam of high frequency in some direction. That's why concert halls are so important as a place for violin performances, because you need the walls and everything within them to reflect those things back out.

Here's one of my favorites. Check out that area in the C-bout, where it's just a little pocket that's going back and forth. By spending a lot of time looking at it, it may be possible that something can be learned.

I now see the violin completely differently. What Stradivari did and what his secret was seem very distant to me now. It is rather a distraction from what we're doing every time we try to make an effective instrument and every time a player picks up a bow and puts it on a string.

Mr. Tao: I would like Tom King to say a few words about Oliver Rodgers.

Tom King: This is the first convention where Oliver Rodgers has not been able to be present. I met Oliver more than 25 years ago when we both were attending a violin repair course taught by Hans Nebel at the University of New Hampshire. From that I developed a very long and close friendship with Oliver. Oliver had an incredible influence on many people. I think that was because he was such a talented man who was willing to work and present things that were very technically based in a way that was easy for any violinmaker to use. And Oliver was one of the very first people who tried to understand how violins move by using what's called finite element analysis. It was at the time an incredibly difficult thing to do and involved very complex computer programming on big university computers.

Oliver didn't have a big university computer, but he was so determined to work this out that he managed to be appointed as an adjunct professor at the University of Delaware. By having that position, he was able to go in, put his programs in, and run them overnight on these big computers. So about 20 years ago he was able to begin showing people how violins actually move by doing this very complex stuff. He continued in this incredibly focused way providing materials of interest. One of the last things that he described at one of the VSA conventions was how one could take little hammers made out of paper clips with erasers and tiny little bits of wood. By tapping all around the violin with these different types of hammers, you could excite, preferentially, different frequencies and begin to see where different aspects of the violin were vibrating at different frequencies. That was very practical, simple, and easy to do. That was Oliver: complex in his thinking about things, but somehow managing to make them in a way that anybody could understand and use.

I miss Oliver very much. I miss the simple contributions that he made. We as a profession are very much indebted to this man with that kind of genius and focus who was able to make things simple.

Mr. Tao: Thank you, Tom.

TECHNICAL RESULTS

George Bissinger: The measurements that you will see were made with a one-dimensional laser scanner that only measures the motion perpendicular to a surface. A 3-D scanner actually measures the motion in the surface. If you had only a flat plate to measure, that wouldn't be a big deal, but we all know that the violin is not a flat plate—it's arched. So when you flex it, it spreads. Only the up/down motion moves the air and creates the sound, while the energy of the in-plane motion just turns into heat.

These motions measured were in one dimension from different directions and then patched together. What makes these animations unique is that they show also the motion of the air in the *f*-holes. The mode called A0 is like what you get if you blow in the neck of a bottle. The bottle doesn't move, but the air inside the neck goes up and down. This is the only big sound producer down on the G-string and the D-string. There's nothing that the body is doing that's involved in the sound of the violin down there. So we made measurements with a little scanning array of microphones over the *f*-holes, and with mathematical procedures, we could predict how much of that energy is going to get to the far field. The far field is about five to ten feet away, not under the ear. Then we made measurements in the far field and found that essentially 100% of the acoustic energy came from the *f*-holes. That was no surprise. That's exactly what some people expected.

Some violinmakers like to tune the neck close to the A0-mode frequency. It turns out that if you do, it doesn't produce any sound because the body hardly moves. I've scaled the pressure readings in the *f*-holes so that they are about equivalent to what the body is doing. So these are two different measurements put together. *[Shown in the video of computer-simulated violin motions for a number of modes discussed below.]*

The dynamic motions tell us an enormous amount. In the C-bout region for the lowest corpus mode I can see a line running down the middle with no motion. On one side it goes out, back and forth. I move up a space and I see that back-and-forth motion, but it's 180° out of phase with this. In the far field, that cancels, because one is pushing air towards you and one is pulling air back, and the sum of those two is zero. So this mode has just three little anti-phase components involving the motion of the top plate and back plate. It's vigorous, but it doesn't produce any sound.

If the *f*-hole air motions would give you some sound, then notice air in one going up and the other going down. So this whole mode, into which a lot of vibrational energy goes, produces little or no acoustical energy. That's a remarkable thing. If you put energy into this mode, you're just warming up the violin and yourself as you play. To be heard in the low frequencies, you want to put the energy into the modes that radiate well.

The 3-D motions show some things that are really interesting. Here's the next higher-order cavity mode A1 in the body of the instrument; the air is going back and forth and back (sloshing). Below it in frequency is the air going in and out of the *f*-holes in-phase for A0. Those two air motions interfere with one another, changing the volume dependence of the A0 mode.

Looking at the *f*-hole air motion for A1, you see that as the lower part of the *f*-hole is going down, the upper is going up, back and forth, resulting in zero net sound radiation. Both sides do this, so neither of these *f*-holes can radiate for this mode. For the *Plowden* this mode radiates extremely well because the internal air pressure variations are pushing the plates up and down, and the plate motion is what's creating the sound. What's going on inside the violin is as important as what's going on at the surface.

Every violin I've ever measured or seen measured has certain modes—called signature modes—underneath the open strings (Fig. 13). Every violin I've ever tested, every cello, and the entire violin octet, every one of them has these signature modes. They all vibrate basically the same way. They have about the same frequency ratios. The cavity mode A0 is followed by the corpus mode CBR, and then A1. Next are the two first corpus bending modes, labeled $B1^-$ and $B1^+$. You may think that this is making the world more complicated for you, but it isn't because everything that's violin-shaped, made out of spruce on the top and maple in the back with the maple ribs (and properly setup) is going to do this.

Let's go to the B1 bending modes. This example is for a student violin, but there's nothing unique about what I'm showing you here. These two modes are the big radiators. Some people like to neglect the lower one and say the upper one is really important, but my measurements don't agree with that. In some of the Old Italian violins, one is higher than the other. If you change the instrument, they flip back and forth. They're both strong, but some are definitely stronger than others.

Here's a mode where the body isn't doing all that much, but you can see air in one *f*-hole moves a lot more than the other. This mode radiates essentially 100% out of the *f*-holes, yet it's not a cavity mode. It's the body squeezing the air and squishing it out a lot more on one side than on the other. There may be air in one going up and one going down, but this one is hardly moving compared to that one. So this puts out a lot of sound through the *f*-holes. One of the remarkable features of some of our measurements is how much acoustic energy comes out of the *f*-holes. It isn't just in the lowest mode, it's scattered all the way throughout, remarkably enough.

A violinmaker just can't tune this A0 mode in any violin without affecting A1. He can't do that without affecting the way it radiates, because these air modes couple to one another. At the same time, you can't just look at what the surface is doing without understanding how it is squeezing the air inside, because so much energy comes out of the *f*-holes. That's what our measurements are showing us, and we've been able to quantify these things.

The VIOCADEAS project came about before there were even 3-D scanning laser systems (Fig. 14). (VIOCADEAS is the acronym for VIOlin Computer Aided Design Engineering Analysis System.) So what I was showing you there is the sum result of everything. Now, here's the thing that is so important that violinmakers should understand. I measure the dynamics and the acoustics and I make all these simulations. Does this help me make a better violin?

The things I measure are particular in one aspect. If I hit something, it moves. If I measure the motion, I measure how hard I hit it. If I hit it twice as hard, will it move twice as much? If that's true, it's a linear system. If it's a linear system, there's this huge mathematical framework, involving what we call normal modes, that enables us to determine how that violin is going to vibrate no matter where you make it move, like with a string or by tapping on the plate. I can tell you in enormous detail what that violin is going to do once I know that and once I know those normal modes. Those normal modes depend entirely on materials. Everything that the instrument can do depends on the materials used in it. You have to know the elastic moduli, which is a term physicists like to use to deal with stiffness. They're the same thing basically. One is a generic way of saying all of the elastic modulates. The other is particular: I'm stretching it, I'm twisting it, and I'm bending it. There are particular ways that it's stiff, depending on what you do with it.

Once you know the stiffness and the density properties, they determine how fast these waves move. That determines how long it will take to make a round trip inside the instrument. That's the period of the lowest frequency wave. Also, when the wave goes out to the boundary and

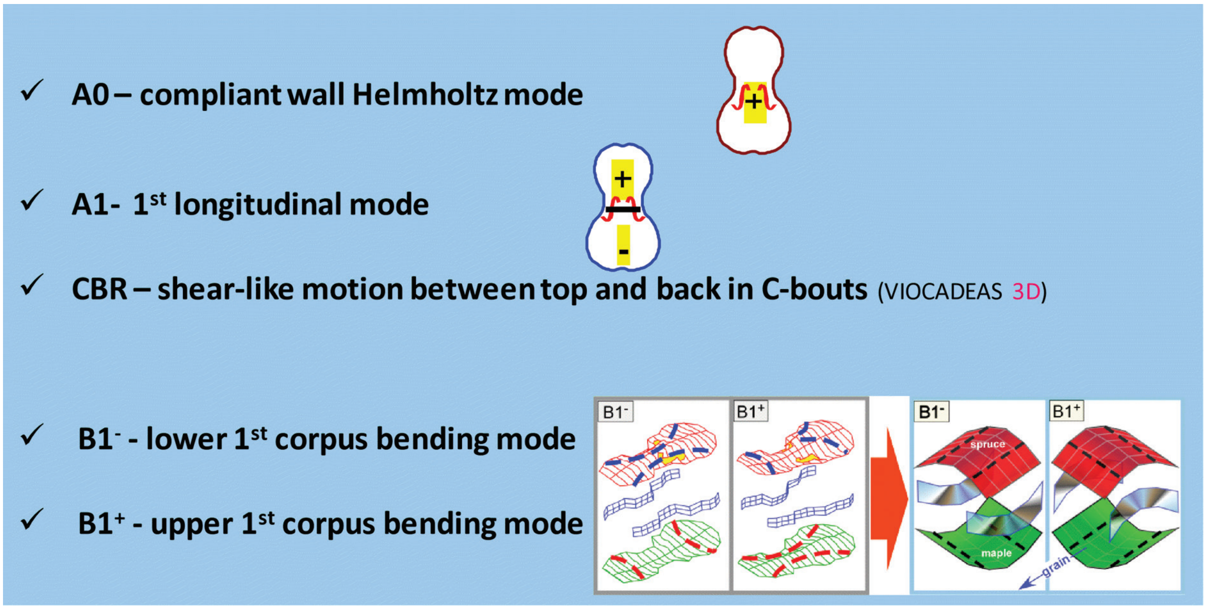


Figure 13. Identification of five "signature" modes of instruments of the violin family. B1 modes with nodal line patterns similar to modes 2 and 5 in the free plates can be treated approximately as flat plates in a simple model to compute B1 frequencies from these two plate modes. (CBR shear and surface motions are illustrated in Fig. 29.)

gets reflected and comes back, the shape of the boundaries determines the interference patterns.

Some of you probably have made Chladni interference patterns, and you know that if you change the shape of your violin plate, you'll get a different shape for the Chladni pattern. That mode shape determines entirely how well it radiates. The material properties, the density and stiffness properties, determine how fast the waves move. The size determines how long it takes to make a round trip. The violin shape determines the interference properties, and the mode shape determines how it radiates.

What VIOCADEAS does is take advantage of the fact that if I know how the violin moves, then I can figure out the materials in a generic sense. Or if I know the materials, I can tell you everything about the dynamics, except I may not know very well the density and stiffness properties of the wood used for that particular violin. So what I do is duplicate the experimental measurements of the vibrations and the sound radiation with finite-element model simulations of that exact same violin. I make those two work together.

This is where the CT scans come in. I didn't realize the value of CT scans for analyzing violin structure for a long time, even though I was in a department that had a medical physics program that did CT scans all the time. CT scans are used to look at pretty pictures inside the human body. What I hadn't understood was that, buried in that brightness diagram, was a number that gave the specific density quite accurately for a particular pixel. The CT scans provide an incredible amount of density information—far more than you'll ever be able to use. Point-by-point, you can see where the patches are, where the glue lines are, where the worms have eaten their way through, etc. It is all there.

The only part of the violin surface motion that we hear is this flexural-bending part. That other in-plane part we don't hear. Flexural wave velocity is about one-third the velocity of sound through one of our top plates in mode 5. When I tap at like 350 Hz and look at the mode shape, I can actually say that's a mode that's flexing (bending) like this. It has like one complete wavelength. Multiply the frequency times the wavelength to get the velocity. It's one-third the velocity of sound. Well, it turns out that the energy in a bending wave that's going that slow, compared to sound, can't be efficiently converted into sound. The essential thing for violins is that that flexural wave velocity keeps increasing with frequency and finally catches up with the speed of sound. At a particular frequency, which we call the critical frequency, almost 100% of the vibrational energy goes into sound.

We measure only three things. We hit the bridge with a tiny force hammer and the violin produces sound. This is in an anechoic chamber, and the scanning laser is directed at a particular spot on the violin (inset in Fig. 14). We hit the bridge with the hammer, the violin moves, we take our velocity measurements, and then the scanning laser moves to another spot. The microphone array picks up the sound produced by that hammer strike, so we're measuring pressures out there. And then, because it's a linear system and my auto hammer was never perfectly reproducible, I take the ratio of the response to the force. Irrespective of how hard I hit it, if it's a linear system, that's a constant. If I hit it hard or softly, the ratio comes out the same. Then I can average it reliably. If you don't do that, you are at the mercy of your hammer technique.

We made near-field acoustical holography measurements (inset in Fig. 14). We spent time with the cavity modes using an aluminum violin cavity filled with water to change its volume to understand what's happening to those air modes inside. Some of these things are very abstract. Makers ask why do I do this? The answer is, you can't do that with a real violin. There are limitations to what we can do.

We compute the motion profiles across the frequency range, which in this case is called mobility profile. It's the ratio of velocity to force. Those little lines sticking up are a measure of how much it moves at any particular frequency at any particular place on that violin. I've put in some red lines here, which are between the regions where the motional lines go up, or go down, where the nodes are. When you produce these Chladni patterns for mode 2 by sprinkling glitter or dust on the top plate, there are two nodal lines that look like that. Anybody who's

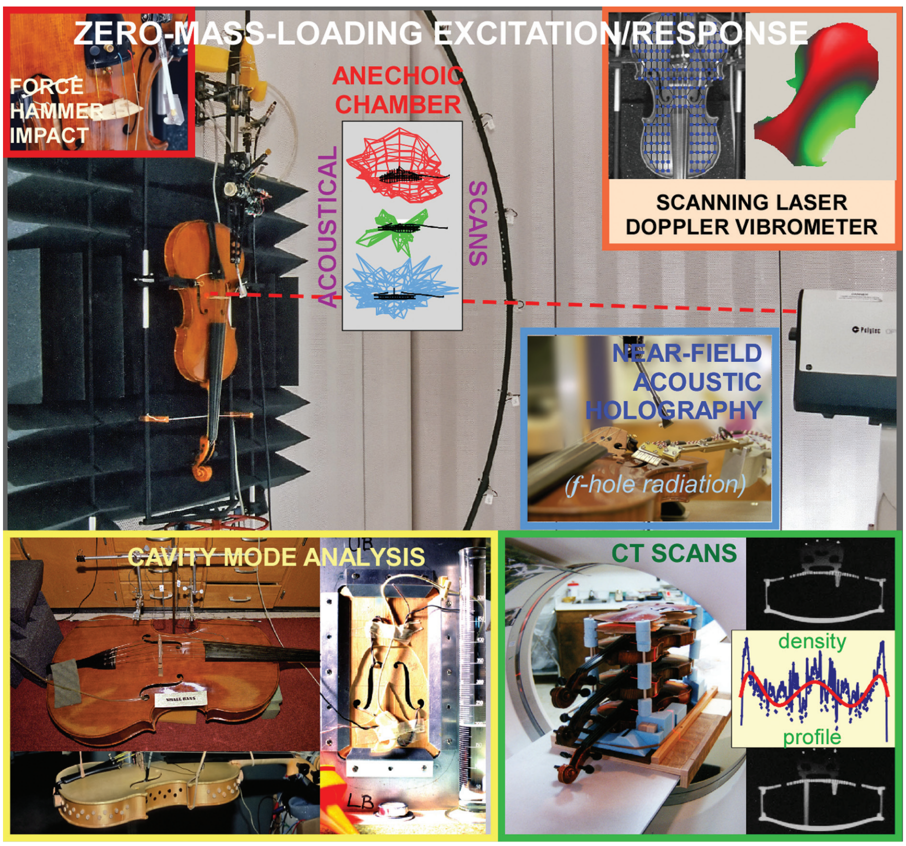


Figure 14. A collage of the various measurements included in the VIOCADEAS (VIOlin Computer Aided Design Engineering Analysis System) Project at East Carolina University.

looked at Chladni patterns on a plate over a loudspeaker knows that the glitter in the areas that are antinodes dance all over the place. The reason they end up at nodes is because there's no motion there. So those nodal lines are a convenient way to characterize them.

The other thing we generate are radiativity profiles. Mode-by-mode they are averaged over a whole sphere. At low frequencies radiation patterns are close to spherical. When the frequency gets up to 800 Hz, all of a sudden it starts to go lobe-y some above, some below. And when the frequency gets up to about 3,000 Hz the patterns looks like a hedgehog—a spike here, a spike there, off the ribs. The output looks bizarre—like one of those things you put in your dryer, such as a ball with all those little prongs sticking out of this rubber ball changing with every mode.

I've also given particular attention to the ribs. In 1996 Martin Schleske performed a very interesting experiment. For his tests he started with a violin with very thick plates with no *f*-holes and no bassbar in the top plate. He glued it together and measured the mode frequencies. Then he took it apart and thinned the plates. In a systematic way in steps, he took it apart and thinned the plates, or cut *f*-holes, or put in the bassbar, re-glued it, and measured the mode frequencies again. So he knew what the individual plates were doing and what the body was doing. His conclusion was, why bother to tune your plates to specific frequencies as it hardly makes any difference to the final mode frequency.

I looked at the same experiment and realized that it indicated that the plates are still influential, but just not very much because most of the bending mode stiffness is in the ribs. So I worked out a simple model that I presented at the Acoustics Workshop at Oberlin College this summer. It's not a universal claim, I must admit, but it's at least a way of looking at a plate. I'm using dynamic modes. I know the mode shape, I know how it bends, and I've turned the violin into a bunch of flat plates that bend in a particular way. The reason I did this is very simple: For rectangular flat plates, there is an equation that allows me to compute the stiffness properly. Of course, the calculations for an actual violin would be much more complicated.

So I look at the patterns, the pressures, and the overall properties of that radiation, and then I put the vibration and radiation stuff together. With few exceptions, most researchers have measured only the vibrations or only the radiation, but not both. However, you can't understand the violin without knowing how each mode radiates. That's what this combination does.

Here's an interesting plot that shows that the fraction of acoustic energy that comes out of the *f*-holes is about 1.0 for the cavity mode A0 (Fig. 15). At the higher frequencies of the B1 modes, somewhat more than 50% of the acoustic energy from those so-called bending modes comes out of the *f*-holes, because those bending modes have large volume changes that squeeze the air out. As the frequency increases, the instrument surface becomes more efficient in converting vibrational energy into sound. At the same time, the amount of motion of the surface goes down, meaning that trend line falls off. Mode-by-mode it goes up, it goes down, hopping all over the place—classic violin behavior. It is astonishing to me how much comes out of the *f*-holes.

The violin radiates in four different ways (Fig. 16): 1) general surface motion that radiates better at higher frequencies than at low frequencies, 2) direct cavity out of the *f*-holes like A0, 3) indirectly, where body motion squeezes the air inside and kind of squishes it out the *f*-holes, more important for low frequencies, not high, and 4) indirectly, e.g. where A1 forces surface motion in a way that radiates very well at specific frequencies.

The important part of this figure (Fig. 16)—the indirect mechanisms—no violinmaker can use anyway because some violins show some of these indirect things, and others don't. We understand direct surface and direct cavity really well. Notice that direct surface has a big broad curve, so that means it radiates at all frequencies, essentially, more or less. That direct cavity peak is where it radiates at one frequency. We've been using this knowledge for centuries in an indirect way, but now we're getting very quantitative. By manipulating material properties, you can address certain aspects of the way the violin radiates in a way we couldn't do before.

Let's talk about damping, which is the way the violin converts energy into sound or to heat. As an illustration, consider pouring energy into a bucket that has only three holes (Fig. 17). The energy comes out as either heat, sound, or to the

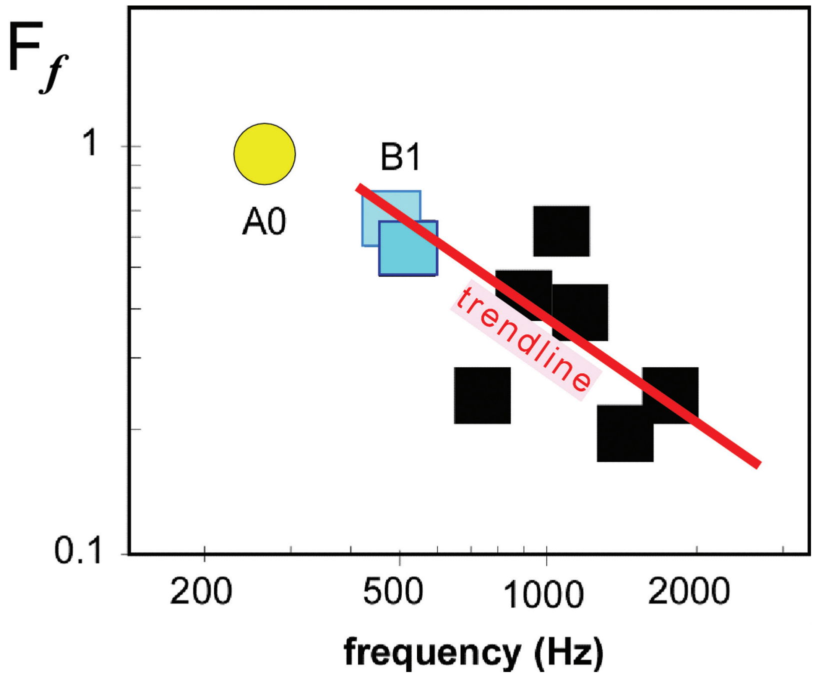


Figure 15. Fraction of violin energy radiated from the f-holes, F_f (computed from ratio: f-hole near-field acoustical holography to total radiativity [anechoic chamber] measurements) versus frequency for strong modes below 2 kHz. (A0 and B1 modes shown in color, higher corpus modes in black.) Trendline (corpus modes only) guides eye toward expected falloff in F_f at higher frequencies as decrease in surface motion combines with increase in surface radiation efficiency to make f-hole radiation less important.

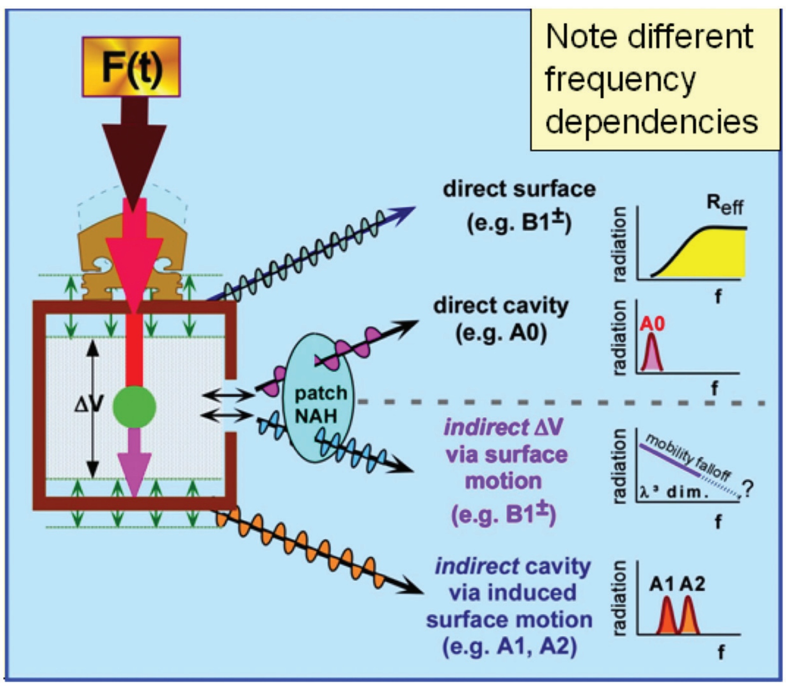
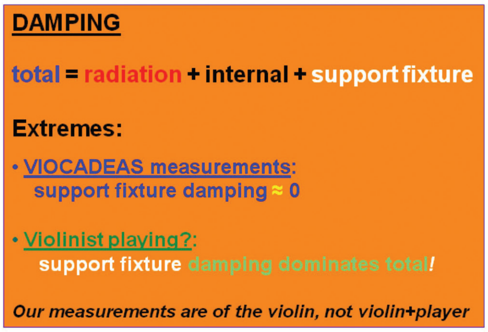


Figure 16. A cartoon indicates four violin radiation mechanisms, each with its own frequency dependence: direct—1) corpus modes from the vibrating surface, and 2) cavity mode directly from the f-holes; indirect—3) from the f-holes due to corpus-motion-induced air flow through the f-holes, and 4) from cavity-mode-induced surface motion.



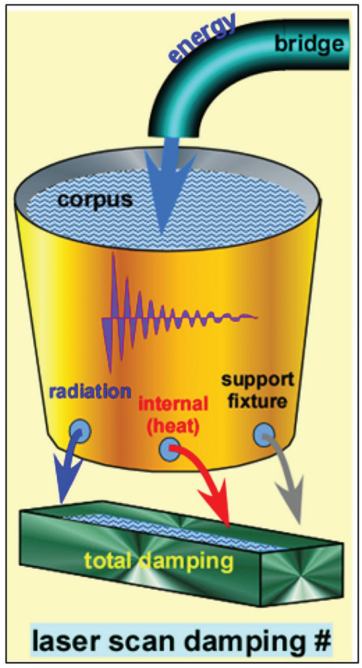


Figure 17. A cartoon of a "leaky" bucket violin losing energy via three leaks—radiation, heat, and the support fixture (representing all the ways a violin can lose energy)—summed into the total damping. If the violin is held as for playing, nominally half the energy is lost to the violinist (the "support fixture").

support structure, which is usually the violinist. In the case of the violinist, about 50% of the energy goes into the body through your shoulder and chin via the chinrest.

Mr. Tao: To demonstrate conduction of sound through your bones you can wear earplugs when you play the violin. You'll discover how much sound comes through your jaws.

Dr. Bissinger: One of the simplifications I've been able to work out for the violin is that there are two major factors in creating violin sound, and only two. One is the bridge, which is where the energy goes in from the strings. The other is the body of the violin, which converts the vibrational energy that comes in through the bridge into sound. They are totally independent of one another.

A few summers ago, Gregg Alf and a team of makers performed a bridge design experiment at the 2004 VSA Acoustics Workshop at Oberlin College. They cut bridges in 40 systematically different steps, mounted them on two violins, and then I measured each step. They trimmed the waist and wings in different ways, which varied the top mass and the rocking mode frequency. Time ran out before qualitative evaluations were possible, so the following summer the experiment was set up to measure only three rocking mode frequency steps. We found out that you can make a very fine violin sound very poor by taking a little too much off the waist of its bridge. My measurements also showed me that a tiny bit of wood taken out of the bridge doesn't bother the body of the violin at all. However, a crummy bridge can render all those hard-won mode frequencies you obtained for your violin made out of the best wood with great attention to detail of no consequence. The bridge is a big factor. I call it the gatekeeper, because it governs how much goes into the violin. You can understand some of the qualitative behaviors of the bridge as a function of its waist thickness by following some of the experimental results we obtained.

Going back to that damping figure with that bucket (Fig. 17), what we measure with the laser is the total damping, which is the sum of all the leaks. Damping gives you an idea of the rate at which the water level drops down—after I bang it with a hammer and put the energy in. That's all damping is: it's a rate of energy loss.

There are three leaks. The net loss rate depends on the rate out of the radiation hole, plus the rate out of the heat hole, plus the rate out of the support structure hole. If I eliminate the violinist (support structure), life is enormously simpler because I plug that hole, essentially, and all I have to worry about is radiation and heat. I can't measure the heat loss directly, but if I measure the total damping and the radiation damping, I can subtract one from the other and get the heat (or internal) damping. That tells a maker about the damping properties of the wood that his violin is made out of. Makers often choose wood by tapping it and listening to its ring. If it goes "thunk" instead of ringing, it is dead and wouldn't be a good choice of wood. You've just done a damping measurement. Surprisingly, we've found that there's not a lot of difference between a good and bad violin. For great old violins and modern violins, that internal damping is hardly different.

Here's the bridge experiment conducted at the 2004-05 Acoustics Workshops (Fig. 18). In the background there are all the bridges we cut and tested. All those bridges with different shapes, trims, and cuts were mounted on the violin, measured, taken off, trimmed, cut, etc. Gregg and his team were up late at night trimming the bridges to be just right, setting up the violin just right, placing them in the test apparatus for measurement, and a few minutes later repeating the process. It was an industrial-level kind of measurement process. Such consistent measurements are enormously effective. Schleske's measurements, where he didn't change the ribs, were the same way—he just changed the plates. The one constant was the ribs. You can work with things that are systematic in a way that you can't work with piecemeal stuff.

Now, let's focus on the idea of a critical frequency. Consider a surfer in the ocean trying to catch a wave. If he just lies in the water, the wave will go right by him because the probability of catching the wave is zero. However, when the

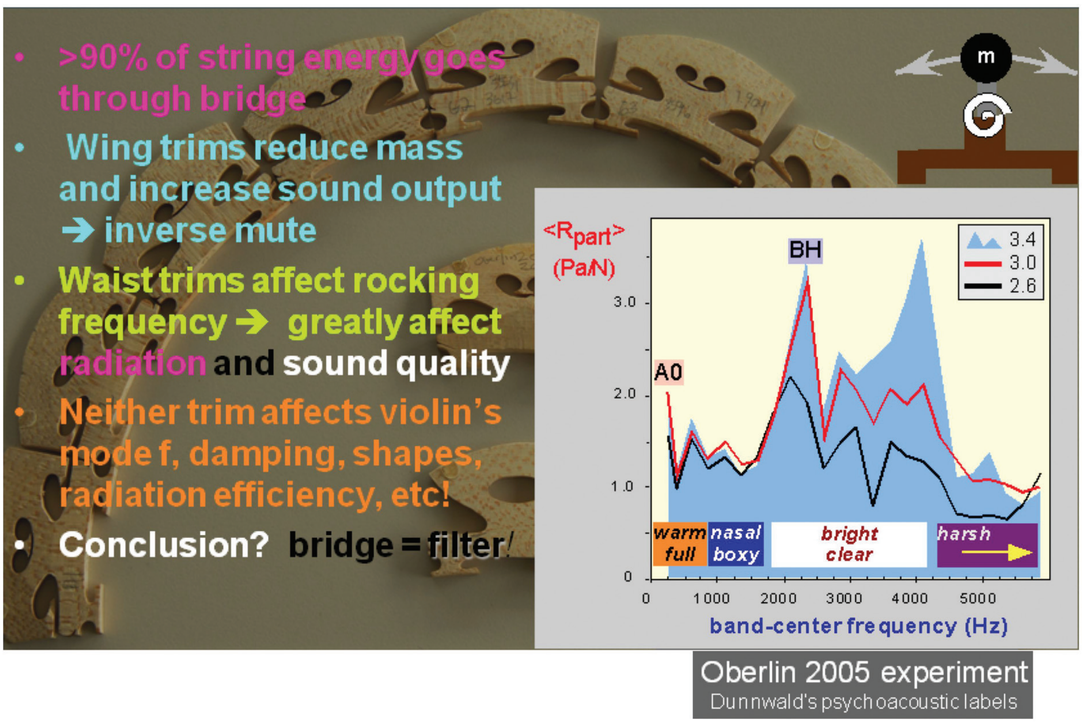


Figure 18. The VSA Acoustics Workshop violin bridge project at Oberlin College (summers of 2004 and 2005) yielded a number of important results. The inset shows the effect on violin radiation spectra by bridges tuned to resonant frequencies of 2.6, 3.0, and 3.4 kHz. (The 2.6 kHz tuning made a fine Andrea Guarneri (1660) violin sound like a student violin; notice falloff at low and high ends in figure above.)

surfer paddles to match his velocity with the wave, the odds of catching it can be about 100%. That's the radiation efficiency curve. When the velocity of the bending wave is way below the velocity of the sound wave, it never catches up with it. The energy stays in the body and turns into heat. As you get up close to that critical frequency the odds of converting the vibrational energy into sound go way up. Now, in the radiation efficiency, they plateau above the critical frequency. (However, if the surfer goes faster than the wave, he gets out in front of it and never catches it, obviously. So there's a little weakness in this analogy, so always stay below the critical frequency.)

What should every maker understand about radiation efficiency? Here's a radiation efficiency curve—essentially, the probability of catching that wave (Figs. 19 and 20). Once you get above the critical frequency, it's flat. That's a stylized version, because for a violin and all typical things radiation efficiency just hops up and down all over the place. Now, here's the radiation-damping curve. I take this radiation efficiency curve and divide it by frequency. As I go up in frequency, the radiation efficiency goes up, but dividing it by frequency slows the rise. Beyond the critical frequency where the radiation efficiency reaches a plateau, that radiation-damping curve goes down. At the critical frequency is the place where the violin is most efficient at turning vibrational energy into sound. That critical frequency depends entirely on the material properties, i.e., the density and stiffness. Once you choose a piece of wood and shape it, the critical frequency is determined by its thickness, elastic modulus, and density.

So is that good or is that bad? Well, this is where the psychoacoustics part comes in. Where do you want to mainly put the sound from the violin? At what frequencies? If you put it up too high, above 4.5 kHz, the violin sound becomes a little edgy and harsh. If you move it down too low, it will sound dull. You've got to put it someplace that adds to the desired quality of the sound. At the same time you have to worry about the excitation, where every higher harmonic is smaller than the previous harmonic and keeps dropping down in a continuous fashion. So the 10th harmonic is 1/10th as big as the fundamental, the first harmonic, and the 20th harmonic is 1/20th as big. The energies decrease with increasing frequency, and radiation efficiency goes up with frequency before reaching a plateau. So there's this going down in energy, going up in radiation efficiency combination where you pump up the acoustic output near the critical frequency. It's really a general destination that we're talking about built on total damping and radiation damping ideas. Does it have anything to do with quality? Well, that's the thing we're going to get into. That's the trail going from vibrations to radiation, an outline of the things I've done up until the time that we started this 3-D program.

We were very fortunate to have the *Titian* and the *Willemotte* Stradivari violins to measure, test, and evaluate because these instruments are remarkably different, which made them both very interesting. The *Titian*, made in 1715 during Stradivari's Golden Period, has relatively low arching. The *Willemotte,* with its significantly higher arching, has an appearance quite different from that of the *Titian*. Stradivari must have been in his 90s when he made it in 1734. What do violinmakers do with their lives if they don't want to keep plowing the same furrow? Well, they keep trying things. Maybe, Stradivari wasn't quite satisfied with what he had done in 1715. He was looking for more answers here. That's the way I think we have to approach this as violinmakers. If Stradivari thought there was still more to get out of a violin by fooling around with various shapes and configurations, we also ought to look at it the same way.

For our dynamic laboratory experiments we needed three lasers to measure the motions in three directions to create a net motion vector. To do the acoustic tests for our out-of-plane experiment, we had to do it remotely because we had to be in the anechoic chamber. You can't stand next to the violin and be in an anechoic chamber because you would block the microphones. So we set up a string to pull the hammer back and let it go. We had to pull strings to test a Stradivari!

Here's a simplified diagram of the violin shell (Fig. 21). You push that shell down, and it spreads out. How much of a difference does that make? With flat plates you don't worry about this, but on shells it's a big deal. That's the general concept behind this *Strad*3D experiment.

Now, I'm going to look at the *Plowden*

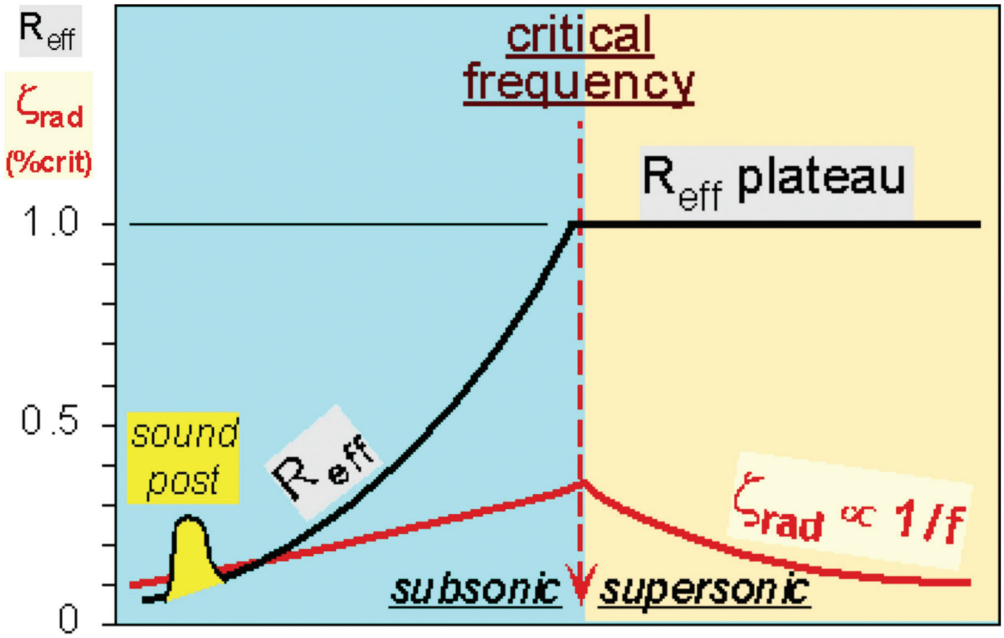


Figure 19. Violin radiation efficiency R_{eff} and radiation damping ζ_{rad} increase with frequency until a critical frequency is reached beyond which R_{eff} is unity and ζ_{rad} declines as 1/f. (The soundpost enhances R_{eff} in the signature mode region.)

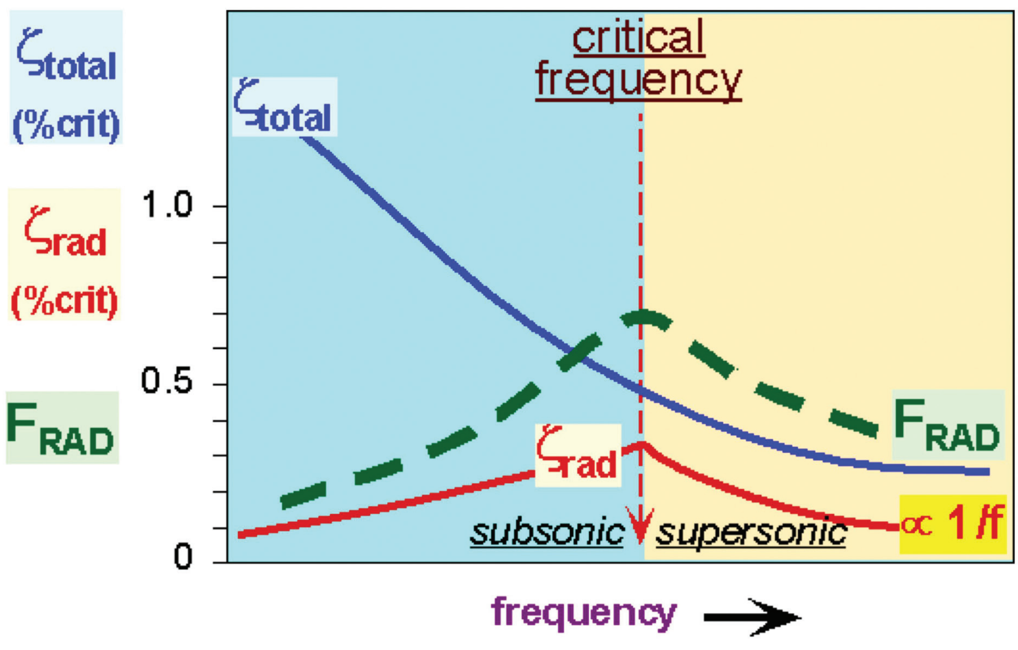


Figure 20. The fraction of vibrational energy F_{RAD} that is converted to sound radiated by a violin increases with frequency until the critical frequency is reached and declines thereafter. F_{RAD} peaks at a nominal value of 60% between 3.3 and 4.8 kHz. Total damping ζ_{total} falls of monotonically with frequency.

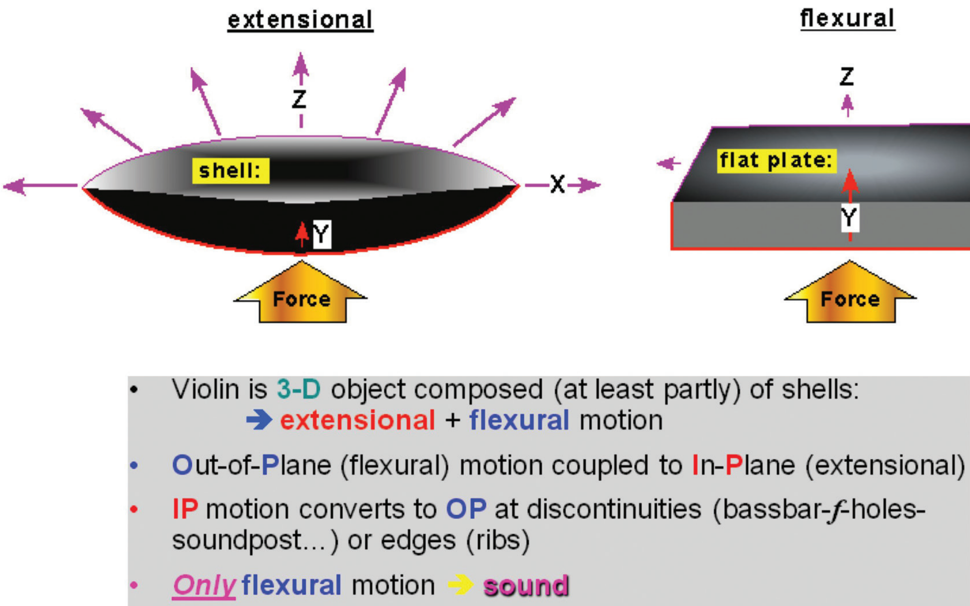


Figure 21. Forces applied to a curved shell cause both extensional (in-plane) and flexural (out-of–plane) motion. Forces applied to a flat plate cause primarily flexural motion. Total damping ζ_{total} *falls off monotonically with frequency.*

because it has one of those things that really amazed me—the very strongest A1-induced surface motion among all 20-plus violins I've tested. It's not that I hadn't seen it before, but it was amazing to see it in an Old Italian violin. You think you understand everything if you measure one violin. Well, you couldn't be more wrong. I've measured the same violin on two consecutive days, and it's behaved as a somewhat different violin. You may be familiar with that effect when the temperature or humidity changes. Sitting in the chamber there, sometimes when I turn on my apparatus and measure a violin a second time, even if nobody's touched it, it's always slightly different.

A feature of the Polytec viewer software is that it allows you to see the motion in a number of ways. I'm showing you the motion the way I measured it with my one-dimensional laser. *[Video animations are shown to the audience.]* Let me pull out this mode. There is the nodal line running down the middle of no motion. You can see one side going up and the other side going down, and it alternates as you go up and down. That one doesn't radiate at all.

Mr. Zygmuntowicz: George, you've selected the y-axis, which means you're only looking at the motion that's out-of-plane.

Dr. Bissinger: Right. Out-of-plane motion. That's what I measured before. I measure that because it's, of course, the sound-producing motion. What you can do is switch that off and do the in-plane motion only. Can you see the difference? We've taken away the out-of-plane motion completely. This essentially produces no sound, but you can see the top and back plates shearing relative to one another. Now, the ribs are like this. I have corner blocks here, and I have C-bouts here. If I were to change the outline, what would I do to this mode? Well, I don't worry too much about it because this never makes any sound anyhow. It's moving like this. What will affect that motion are the corner blocks, how deeply in-curved the C-bout region is, and anything that will stiffen it against sheer motion. If you want to move it up, you make those curves a little bit more extensive.

All the viewer program features Sam that uses to select which direction to go are all fully functional on the DVD, and all these files are on there as well. That is one of the virtues of the *Strad*3D DVD. You're looking at a world no one has ever seen before in violin making or in vibrations on the violin. You can now look at a mode of vibration that you can understand. Is it doing this, or is it doing that? Let me go up a little bit and keep the in-plane motion along the z-direction, the long direction. And then you ask are the plates doing this kind of stuff? What do my end blocks look like? How fat are they? How wide are they? Anything that affects this kind of motion, the blocks, two plates, blocks at the end, and whatever else there is that affects that motion. You start to get physical insights about what it's doing. You are able to look at how it's moving mode-by-mode.

Audience member: You said there was something unique about the *Plowden* in this particular motion.

Dr. Bissinger: We're looking at it from the side, lower bouts on the left, upper bouts on the right *[playing video of 3-D violin dynamics]*. Notice how fat the lower bout is above the unformed shape. The upper bout is in the opposite direction, but it's just a little bit below. It's like a big sphere, expanding and contracting. And here it is like a little sphere expanding and contracting. What you hear out here in the room is going to be totally dominated by that. It's like a monopole, just like an expanding, pulsating sphere—an efficient energy radiator. This is the biggest of any instrument I've ever tested. The *Titian* has hardly any of this, but on the *Plowden* this is a major significant radiator and it broadens the lower first corpus bending modes. When you put the fundamental on top of that, instead of this one peak, there are two peaks. So you can get two, three, four notes inside of that envelope—a strong response.

Sam has mentioned that the *Plowden* has a wonderful mellow tone. That doesn't come by putting a lot of energy into the high frequencies. It comes with putting it in the lower ones. Yet, this is a mode that violinmakers don't use, in general. Carleen Hutchins tried to use it, but not very well because it was just a frequency thing for her and it didn't tell you whether it was a strong or weak response. I wish I understood why this instrument does it and others don't.

Mr. Zygmuntowicz: When we sent these instruments through the CT scan machine, they were stacked up one on top of another. It was very apparent that the *Titian* has a huge bassbar, which you can see in the CT scan pictures, and the *Plowden* has one of the smallest bassbars (Fig. 3). Aside from what other Strad/Guarneri differences there are, the big difference in the sizes of the two bassbars is something that you can see physically that you can at least postulate is influencing this.

Dr. Bissinger: That's exactly what you want to look for. Why is this one doing this and the others aren't? You start to look at things that stiffened it on the long direction, and the bassbar is obviously a big stiffener.

Here's a plot, just like some of the things that Sam showed, showing the response of the *Plowden* Guarneri (Fig. 22). We included in the DVD the Excel files of all of the instruments that we tested with the vibration and the radiation. These curves are included and I've annotated them. And down here, this is the *Plowden*, and there's the peak of the A0 mode. The lower blue curve is the mechanical motion in velocity-per-unit force in meters/second/Newton. It's calibrated.

Above is the radiativity, the amount of sound (per unit force at the bridge) it produced in the anechoic chamber, 1.2 meters away, averaged over a sphere. So this is the average stuff, which is pretty much what I deal with. It's much more complicated at higher frequencies, and I cannot figure out what I should do with it. That's why I averaged over it, which eliminated the problem. Comparing the top hemisphere radiation to the back hemisphere gives a violinist playing in an auditorium a sense of what's going out like this and what's bouncing around before it gets out into the auditorium.

If I were to pull this figure out and compare it to bad, good, etc., violins, you'd find nothing exceptional in this figure. It's not bigger and it's not smaller. The peaks are at different places, but there's not anything exceptional about it. If you look at the radiativity curve in units of pressure per unit force, nothing is unusual about that either. The *Plowden* in no way stands out in terms of loudness.

The one thing I didn't mention is that it has that A1-mode peak. You can see that the A1-induced mechanical motion is actually a little bigger than the direct motion of the first corpus bending mode. And there's the radiativ-

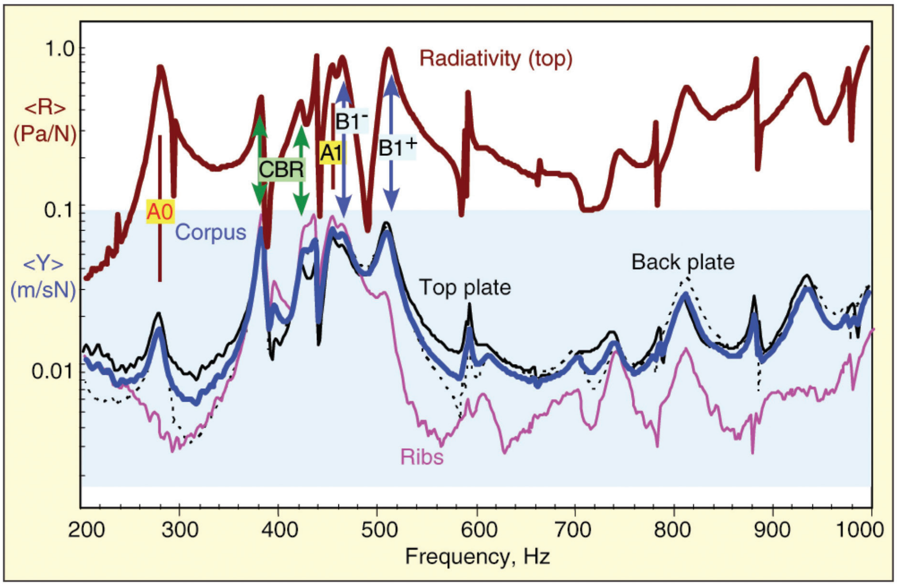


Figure 22. A "spaghetti" plot overlays the measured averaged-over-top-hemisphere radiativity (<R>) and out-of-plane mobility (<Y>); area-weighted-average over corpus (top+back+ribs) spectra of the Plowden *Guarneri* del Gesù *violin. (Narrow spikes are undamped string resonances; signature modes below 600 Hz are labeled: cavity modes A0 and A1; corpus modes CBR, $B1^-$ and $B1^+$). A1 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 the 400-500 Hz region. (All violins were measured on elastic band supports, i.e., "free-free," with undamped strings.)*

ity. There's a double hump in there, so it really broadens the response in that region.

I should point out that the separation between those two curves is a direct measure of what we call the radiation efficiency. I measure the radiation and the motion and take the ratio to compute the radiation efficiency. But it has to be calibrated numbers, pressures and velocities, divided by force.

Looking at the good versus bad, is there something unique about Old Italian violins? If you're a violinmaker, you've (probably) never really worked with these curves. Let me tell you a little bit about this. Every one of those peaks corresponds to a particular way of vibrating. The frequency tells you just where to find that particular mode of vibration. It's like Chladni patterns. For mode 2 in the top plate, you look around 150 to 180 Hz, and for mode 5, you look around 340 to 350 Hz. You go to certain frequencies for certain patterns. The width of that peak is a measure of the damping. The wider it is, the higher the damping. When a violinist holds that violin, the peaks won't move in frequency much, but their amplitudes will drop and the widths will spread. It would spread so much that once you get above a certain frequency, there wouldn't be separate peaks. Every one of these bumps would overlay another bump. So above a certain frequency, I pay no attention to individual modes, because I know when the violinist holds and plays it, I wouldn't be able to find them anyway. At lower frequencies, however, the signature modes can always be picked out.

The body of the violinist is a damper and makes it difficult to figure out what the violin is doing. So if you want to measure the violin, you've got to exclude the violinist. You have to float the violin. What we're finding out is that there are very little differences between the violins. That's the point of some of this work.

I have plotted total damping, the radiation properties, the internal damping versus frequency for two Old Italian violins and 12 modern violins, good and not so good (Figs. 23-25). I have used band averages because it's a lot smarter to do that instead of trying to do every mode for everything. The 12 modern violins are more uniform in behavior because there are 12 of them, not just two. In small-number statistics, typically things hop up and down. I put in the error bars for the 12 modern violins, and when they overlap there is no significant statistical difference between them. I wouldn't ever want to go to one band and say, yes, this is really different.

It's remarkable that there is generally more total and internal damping at low frequencies than at high frequencies (Figs. 23 and 25). Most people don't understand that. Looking at the values in the Haines Table of Material Properties (*CAS Journal*, Vol. 4, No. 2, pp. 20-32 [Nov. 2000]), you see the damping going up with frequency. The problem with those measurements is that they were made on little bitty strips, and at very low frequencies, they don't radiate at all. But at higher frequencies, the wavelength comes down to about the size of the object that's vibrating, and they start to radiate. So when you hit something like this, it's got the lowest mode at about 200 to 300 Hz, you hardly hear that, but up around ~2 kHz, you really do hear it. So you might hear a higher pitch, per se, and the smaller you make it, the higher that pitch.

The damping properties of isolated parts are not the same as conglomerate objects, things glued together. This is where the joint problem becomes important. How do you glue your top plate to the ribs? How wide is that lining strip? How much glue do you stick on there? Do you really press the glue out between the plate and the rib? Is the joint like wood-to-wood, or is it wood-to-glue-to-wood? The reflection of a sound wave at a boundary is different from glue than wood, so the modal pattern will be affected. These are the details that violinmakers should to pay attention to.

Audience member: What would you generalize about the difference between reflection back and dissipation? For instance, comparing thinner edges and more flexible ribs versus stiffer edges and stiffer ribs.

Dr. Bissinger: If I take a string and tie it to the wall, that end is fixed and it can't go anywhere. So whatever wave I send there gets reflected and comes back, but that point on the wall doesn't move. But if I tie it to a rubber band and then tie the rubber band to the wall, and I send that wave down, the end is free to flop around. The wave gets reflected entirely differently if it's tied to the wall versus free to move. If the sound wave

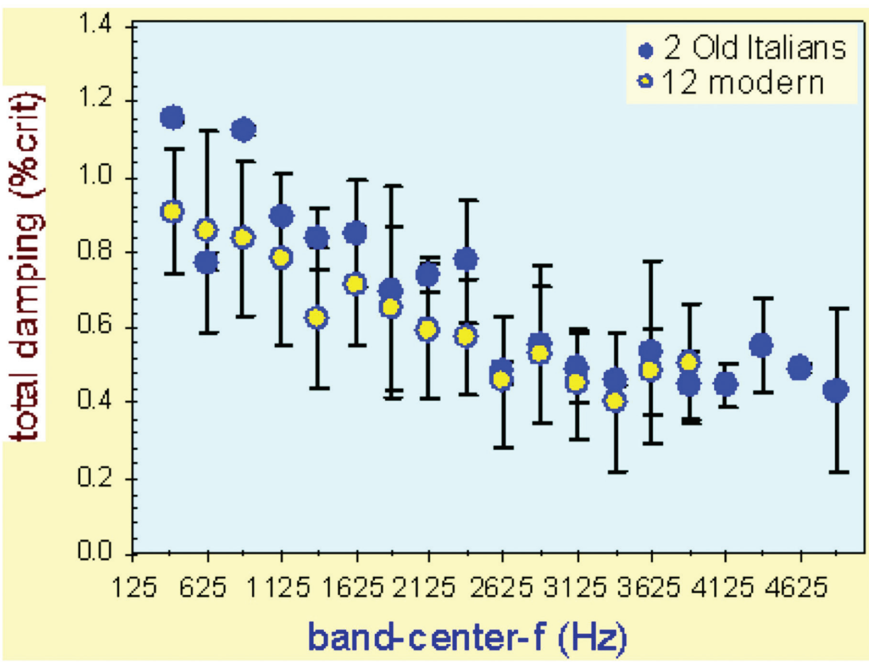


Figure 23. Average total damping ζ_{total} for 12 modern violins (○) and two Old Italian (●; Titian Stradivari*, Plowden* Guarneri *del Gesù) violins. At frequencies < 2 kHz, ζ_{total} for the Old Italian violins was generally higher. (When error bars overlap, difference is not statistically significant.)*

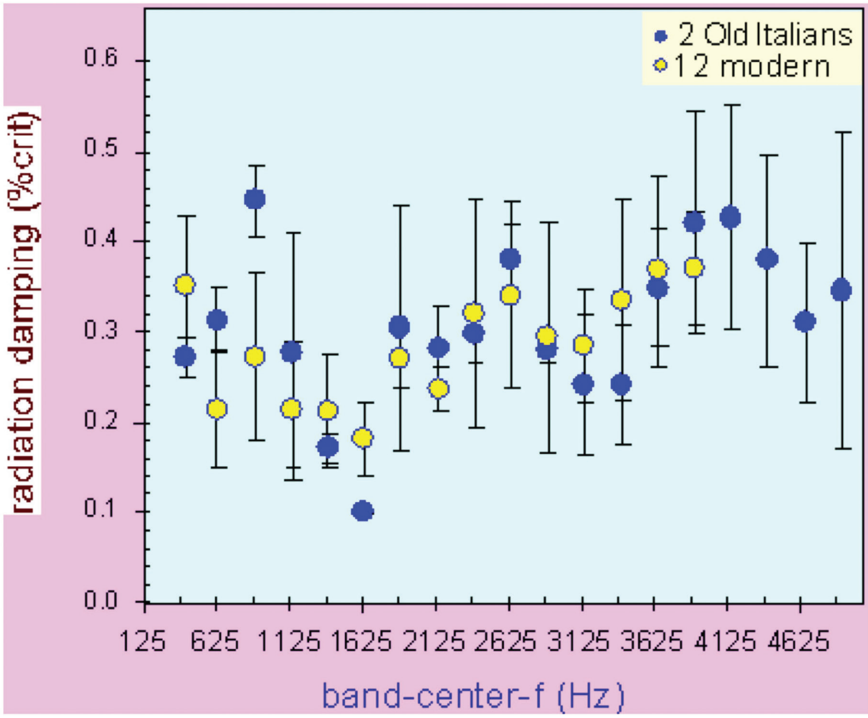


Figure 24. Average radiation damping ζ_{rad} measurements versus frequency for 12 modern (○) and two Old Italian (●; Titian Stradivari, *Plowden* Guarneri *del Gesù) violins. No consistent correlation with total damping ζ_{total} was observed. (When error bars overlap, difference is not statistically significant.)*

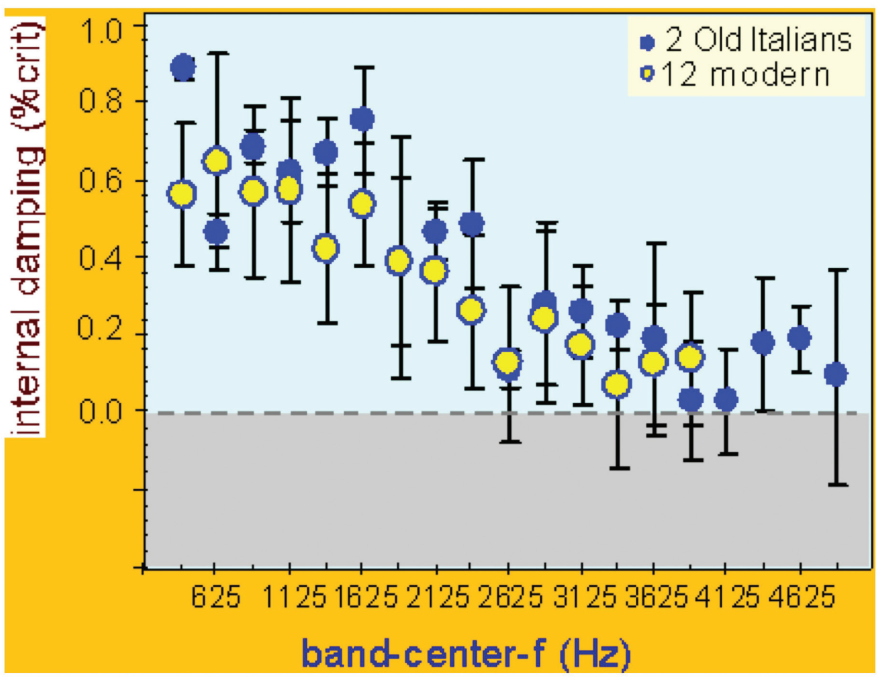


Figure 25. Average internal damping ζ_{int} (calculated using $\zeta_{int} = \zeta_{total} - \zeta_{rad}$) versus band center frequency for 12 modern (○) and two Old Italian (●; Titian Stradivari, *Plowden* Guarneri *del Gesù) violins. Values of ζ_{int} for the Old Italian violins were generally slightly higher. (When error bars overlap, difference is not statistically significant.)*

strikes a wood-to-wood joint of exactly the same materials, it essentially doesn't get reflected at all. But if it strikes a wood-to-glue interface, with the glue having a higher density than the wood, it will get reflected in a different way. So the quality of the glue joint, how uniform that surface is on the underside, and how much the glue has been excluded can make a bit of a difference. I'm not going to say it's a huge difference.

Audience member: What's the implication of it getting reflected as opposed to no reflection?

Dr. Bissinger: It likely changes the mode shape, not the frequency. If it changes the mode shape, it can change the way it radiates, which means it's going to change the way it sounds a little bit. If you were to remove the top plate and then immediately glue it back on, would it sound exactly the same as best you can remember, or a little bit different? The players face a different world than us experimenters, but we can look at what you face in the practical world and make some general comments based on our understanding of what waves do inside materials. You may bend it, weigh it, and measure its volume. We're looking at it in a dynamic world. Everything is moving, but the static properties that you measure are the ones that determine how things move.

Knowing some of the basics is a great help here. Radiation damping has nothing to do with the total damping in the sense that each is determined from different parts of the experiment, and radiation damping contributes to total damping in a totally independent way from the internal damping. To compute radiation damping you have to know the radiation efficiency using the pressure-velocity ratio, the frequency, and the violin total mass.

Audience member: Is this radiation damping or total damping?

Dr. Bissinger: Radiation damping.

Audience member: So this doesn't mean that the old violins absorb more sound; it means that they're getting the sound out into the air quicker and more effectively.

Dr. Bissinger: Yes. A crucial point about damping is always energy loss. It's always the way it loses energy, the way it leaks out. It has nothing to do with how you put it in, like through the bridge. It just says there's so much vibrational energy that leaks out.

Audience member: If there's higher radiation damping, with more sound getting into the air, does that imply that there is less viscous damping?

Dr. Bissinger: No, but it's a component of the total damping. It's computed in an entirely different way, and that's what I mean by independent. I measure the pressure here, I measure the surface motion there, and take that ratio, divide it by frequency, and divide by the violin mass. I've never used that plot you just saw with all the peaks and bumps and the spreads. I don't touch that at all. I only pay attention to the separation between those curves. I pay no attention to the width of those peaks. This is a different world entirely. Radiation damping is the way the violin loses vibrational energy to radiation. That's one leak. The other is heat, and we're going to get to that next.

Audience member: Are you saying that a lot of sound gets out of those Old Italian violins fast?

Dr. Bissinger: Yes, in the sense that the total damping is slightly higher, but the question is not as simple as that, because what you don't know is how much you put in and what percentage of it is going out as sound. If the total damping is higher and the radiation damping is higher, the fraction that leaks out the soundholes in that bucket could still be the same. Even though it has higher radiation damping, it does not necessarily mean that it puts a higher fraction of its vibrational energy into its sound. I'm going to get to that, because you can compute that from the damping. This is the egress field we're talking about here.

How does the violin lose its energy? That's how you are heard. The gatekeeper pays attention only to how I get energy into the violin. The egress pays attention only to how you get it out. So there's the radiation damping, and they're not all that different. It's up, it's down, and it's pretty wiggly. There may be patterns there if you put in the psychoacoustic terms like nasal, bright, clear, harsh, warm, and full sounds. To determine the internal damping, I subtract the radiation damping from the total damping.

There are two Old Italian violins, and why not three? The answer is we couldn't do this calculation unless we had made a whole-body measurement, including the top plate and back plate. For the *Willemotte* we had data only for the back plate, and for Curtin's violin, we had data only for the top plate. So I couldn't do the calculations for those two violins. You have to do the whole surface to get some idea of the motion of the whole surface, to be able to take that ratio.

You can see a little bit of difference between internal dampings, sometimes a little bit less, sometimes more. The errors are big because I'm subtracting two fairly bouncy numbers (Fig. 25). Is that statistically significant? With only two Old Italian violins, I wouldn't want to claim anything based on those curves. The errors are telling me not to make too much of this. My presumption is that old and new woods are basically the same in terms of their damping properties, assuming that's where most of the damping takes place. And once I know that, the increased total damping is not due to increased internal damping. This came to mind because Joe Curtin told me that when he tapped a lot of Old Italian plates, they sounded so dead. And I said that we ought to be able to measure that. Well, this is telling us that for these instruments, at least, there was not much difference. What does that mean? When I hang the violin from these little elastic bands, essentially none of its energy is lost to the support. But when a violinist plays it, he absorbs about half the energy that he puts into that violin. At low frequencies internal damping dominates as a percent of the energy loss, but internal damping falls off with frequency, as you saw in that curve. So that means most of the total damping at higher frequencies is radiation damping.

Here is an interesting point. The violinist actually emphasizes the difference between good and bad violins by holding and playing them. This comes from the mathematics of damping. It's just a ratio of radiation and total damping numbers $\mathbf{F}_{RAD}$. If I measure a violin with no support fixture damping, there is no loss to the support. Then when a violinist holds it, 50% of the energy applied during playing goes into the violinist as heat. You might think that just drops the fraction $\mathbf{F}_{RAD}$ down by a factor of two. Indeed it does, for both good and bad violins. It's when you compare good to bad, the relative ratio of $\mathbf{F}_{RAD}$ values, that it turns out to be approximately the ratio of the radiation damping. Then Sam's remark becomes relevant. It does make a difference. It is putting more out there in terms of sound. But the fraction $\mathbf{F}_{RAD}$ is hardly different because for my free case, you have to take the radiation damping, which for the Old Italians is also higher, and divide it by that total damping, which for the Old Italian violins is higher. So in the ratio with my trend lines, with the large variations smoothed out, the bad violins and two Old Italian violins $\mathbf{F}_{RAD}$ values are pretty close (Fig. 26). I took my three worst sounding violins, and that's the trend line for those. And there's the trend line for the best two. There's not a big difference between these radiated fractions. It can be more than 100% since the errors are so big. 100% is where all the vibrational energy goes into sound, and 0% is where all the vibrational energy is converted into heat. At low frequencies, about 20% goes into sound, and at high frequencies, we're getting 70 to 80% as sound radiation. That gives you a sense of how good you can be. The difference between these two trendlines is due essentially to their different critical frequencies.

Audience member: One of the places where we see the biggest differences is at the very low frequencies where the Old Italian violins are higher, and very much lower in the nasal region.

Dr. Bissinger: Yes. And now you're talking about the radiation (or radiativity) profile. That's a crucial distinction there. The trend lines don't mean much, except in the sense that I use them because they relate to that radiation efficiency curve and the critical frequency. So if you lower the critical frequency, you boost up everything below it relative to a higher critical frequency.

There are the choices of materials with their elastic moduli, densities, and plate thicknesses. If you make the plates too thick, you can lose much of the desired physical response to that driving force. We always have *F=ma*, so with a larger

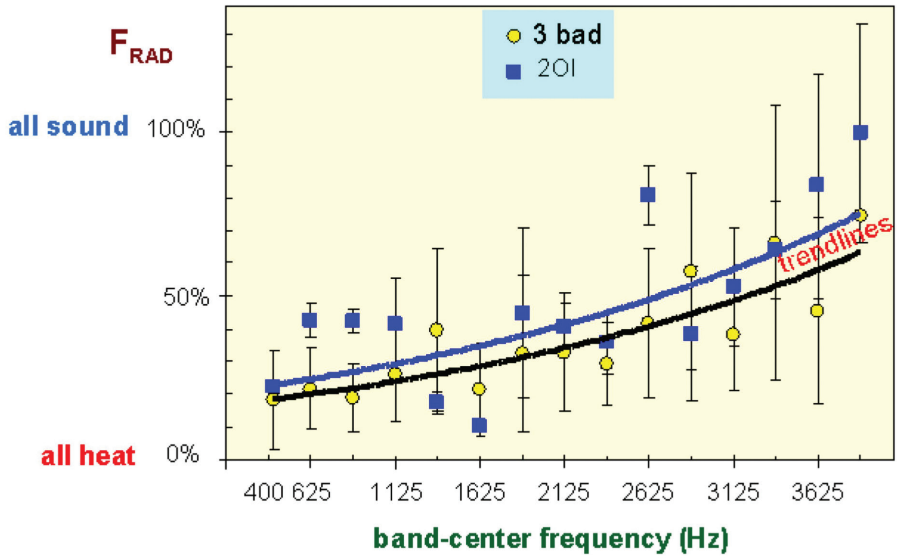


Figure 26. Fraction of vibrational energy radiated as sound versus frequency for three bad (○) and two Old Italian (■; Titian Stradivari and Plowden Guarneri del Gesù) violins.

mass *m* there will be a smaller acceleration *a*, for a given force. This force comes from the strings. You want the violin to be lightweight, but in such a way that it will put the critical frequency where you want to get the maximum response from the egress filter.

Here's the effect: Differences between the Old Italians, our best instruments, and the bad ones really start to show up here (Fig. 26). Still, the errors are large. Here's the computed ratio of the fraction turned into sound $\mathbf{F}_{RAD}$ and here's the ratio for the radiation damping. When the violinist holds the violin, half of the energy goes to heating up his shoulder and/or chin. Even then, in a relative sense, it doesn't make any difference because this is the ratio of radiation efficiencies, which for the Old Italian violins was larger than for the poor instruments that you saw in that previous curve.

Here is a free/free situation, where I suspended the violin by elastic bands, and here it is when held by a violinist (Fig. 27). You can see that being held by the violinist enhances the difference between good and bad because of the way you compute that ratio. These are purely from crude mechanical damping models. They're not specific. They're general kinds of things and just fundamental physics. As a maker, you have a way to kind of use that filter, move it around a little bit by your choice of materials, by adjusting that critical frequency.

I mentioned that the violin radiation at higher frequencies looks extremely spiky, so I put in a plot at 3,300 Hz. There are 266 microphone positions in there, and you're looking at it from the side. One of the interesting things is that it doesn't do as much overhead as it does out here. But look at how spiky that is—there's no simple shape to it. Here it's really strong, but right next to it angle-wise it's really weak. It goes out strong, it's weak, it's strong, it's weak, etc.

The virtue of a good auditorium is that it homogenizes the sound, boosting up the bass and cutting down the treble, relatively speaking. A violin like the *Titian,* which up close is a bit bright, is a perfect instrument in an auditorium because of its brightness. It gets the bass boost where it's a little weaker than the *Plowden*, and it drops down the very bright part, relatively speaking. So in a big auditorium, that's a positive.

Another property is the directivity. If you are a violinist playing in front of a full orchestra in a large auditorium, you will produce a radiation pattern. This is for one mode, but for the high-frequency modes, in general, it will get to be really spiky. But understand that when you get out into the auditorium, everything bounces around, and it makes no difference. So all you care about is some kind of average directivity.

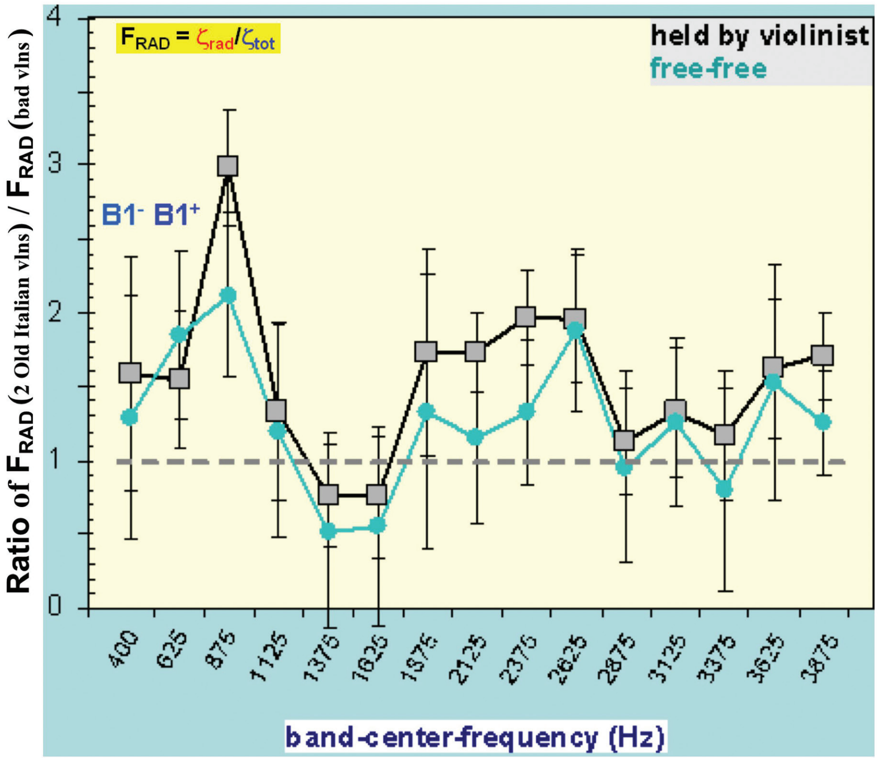


Figure 27. Ratio of F_{RAD} (two Old Italian violins) / F_{RAD} (bad violins), where $F_{RAD} = \zeta_{rad}/\zeta_{total}$.

Here the violin is radiating sound out into the auditorium. The audience hears the sound both directly and after it bounces off the walls. The violinist, of course, wants to be heard. Consider the number of bounces the sound might take. Here's a simple model. From the top plate (the radiation is stronger from the top) the radiation bounces out once, twice, and it's down in the audience where the ears are. Sound radiated from the back plate hits the floor. It bounces off the back wall or the orchestra, then goes out, bounces around and comes back to the ear. On every one of those bounces some of the sound is lost, because surfaces absorb acoustic energy. Having two extra bounces, especially if there's a full orchestra behind you, pretty much sucks up what the back plate radiates. That's the reason why soloists hold their instruments in such a way to be better heard.

Did the sound from these instruments we tested vary in directivity? That's a good question. Let me show you the directivity for 17 violins, bad to exemplary (Fig. 28). Included are Curtin's violin, Zygmuntowicz's violin, the *Titian,* the *Willemotte,* and the *Plowden*—two modern and three Old Italian violins. We made a complete set of acoustic measurements on all these old instruments. We looked at what went into the top, on the average, divided it by what went in the back, on the average. A ratio larger than one means the top plate is radiating more than the back plate.

At the lower frequencies the ratio was less than 1.0 for some instruments, maybe about 20% less. It's not a big deal because the auditorium will boost the lower end anyway. Here's the *Titian,* the *Plowden*, and the *Willemotte*. The *Willemotte* was the least directive violin I've ever tested and the *Titian* was the most directive. The *Willemotte* had about the highest arch of anything I've tested, and the *Titian* had a rather low arch. With a flat plate, there's not much in-plane motion. It's just basically all out-of-plane. The more you arch it, the larger the in-plane part gets to be when you make it bend. Going like this is a bad thing for a violinist if you want to be heard in a large auditorium. On the other hand, if you're in a room this size, you may not care. So your performance requirements are going to drive your arching. There's no one perfect violin for every application. As a maker, you get

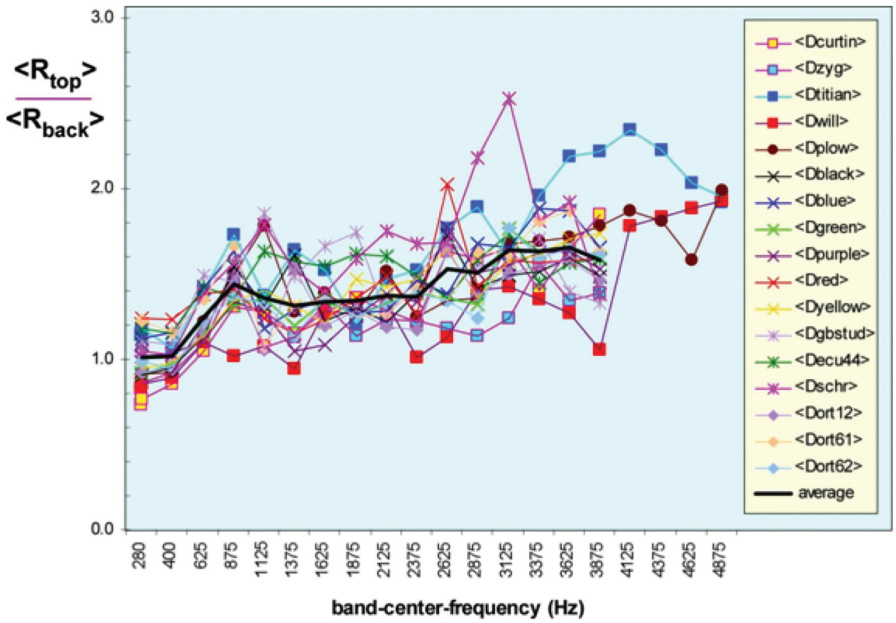


Figure 28. Measured directivity (ratio of averaged radiativities of the top to back hemispheres) for 17 violins, bad to excellent, versus frequency. The Titian *had the highest directivity, the* Willemotte *the lowest, while the* Plowden *was about average.*

to choose your arching and your materials, and so you can move these things around. With this information we have now, you're starting to get a handle on things that you can do.

Mr. Zygmuntowicz: At the end of our trip to North Carolina, we had heard all the violins, the three Italians plus Joseph Curtin's violin and my own. Joseph's violin was a Strad model with high arches, and my violin was a Guarneri model with flattish arches. Sound-wise, we thought that Joseph Curtin's violin was in the same family of sound as the *Willemotte,* which is also a high-arched fiddle. I don't know if the other participants would agree, but I thought my violin was in the same family as the *Titian.* In the radiation spectra from the impact hammer tests you see the spectral shape of a high-arched violin and the spectral shape of a low-arched violin. So you do start to have a clear pattern of the types of arches and types of sound.

Mr. Tao: It goes a little further than that, because when I played it, the response that I felt was also more similar in that vein. When I played Sam's instrument, it was more similar to the *Titian* in terms of the way it felt and responded. Joe's instrument was closer to the *Willemotte.*

Dr. Bissinger: Now, that's the kind of stuff we don't measure, of course. We don't measure people on purpose because we're after the violin's characteristics.

Mr. Tao: But the way we tie it all together is—without a subjective judgment of the violin—you need a subjective violinist to know what you're trying to technically describe.

Dr. Bissinger: Exactly. The violinist is the bottom line, and you have to work backwards. But if it's the violin that's really the big deal and not the violinist, we should be seeing pretty substantial differences between good and bad violins.

David Chrapkiewicz: I think that what you're saying is if you reduce the in-plane motion of the plates, you allow the energy to go more out-plane. One way to reduce in-plane motion is to use lower arching. Are there any other notions you might have?

Dr. Bissinger: I've talked to some people at the Naval Research Laboratory who worry about how submarines radiate. They pay a lot of attention to in-plane motion because it doesn't produce sound waves in water as much as out-of-plane motion. There is no simple prescription, but their measurements indicate that if you put the energy in out-of-plane, some of it is going to end up being in-plane no matter what you do. If you put it in purely in-plane motion, some of it is going to end up being out-of-plane, because those two motions are coupled. Discontinuities like edges, bassbars, and soundposts can convert in-plane motion to out-of-plane motion (and vice versa), because at the boundary, that's where incident and reflected waves meet. The incident and reflected wave. If I were a violinmaker, I would love to be able to manipulate that out-of-plane to in-plane ratio, because that changes the directivity. We have enough measurements here to relate that to our out-of-plane/in-plane measurements. The structural acoustics tells you that out-of-plane motion is what radiates, and that in-plane motion doesn't produce anything. *[Figure 29 shows selected images from the Strad3D DVD for both out-plane and in-plane motion of the* Plowden *Guarneri.]* So you expect the ratio of out-of-plane to in-plane motions should be significant. We just showed you directivity, which relates the radiation above and below.

We have measurements of the ratio of out-of-plane to in-plane motion for only two violins (Fig. 30). Fortunately, the *Titian* was much different than the *Plowden*. Look how high out-of-plane to in-plane is for the top plate for the *Titian* relative to the *Plowden.* And then look at the directivity for the *Titian,* which is the red curve versus that for the *Plowden*, which is pretty close to average. So these are factors in terms of radiativity say in the region around 3 kHz. There is a fairly substantial difference in the spectral region of 1.3 to 1.8+ kHz where the ear is really sensitive. If I were a violinist playing in front of a large audience in a big auditorium, I'd want an instrument to radiate out of that top plate in the 3-kHz region really well, compared to other things.

Audience member: Yes. And those types of measurements you and other people have been making for a long time. The significance in terms of this project is that, for the in-plane and out-of-plane motions, you can only get that with a 3-D laser scanner.

Dr. Bissinger: That's right. So this is a unique result right now: that you could look at the out-of-plane and in-plane motions and get some idea about the radiativity, the directivity. The back plate is hardly different among the three Old Italian violins. So any difference in directivity would be in terms of the out-of-plane to in-plane ratio. That may be why the back plate, even though it's a significantly heavier plate, is able to participate better in the radiation from the violin than you might expect from purely weight consideration, because it's got a higher out-of-plane to in-plane ratio. That tends to compensate for the fact that it's not moving as much. More of its motion is in the bending wave, the sound-producing part.

Deli Sacilotto: My understanding has always been that lower arching resulted in greater volume and that the higher arching, like a Roman arch, has considerable strength to it and limits the vibration.

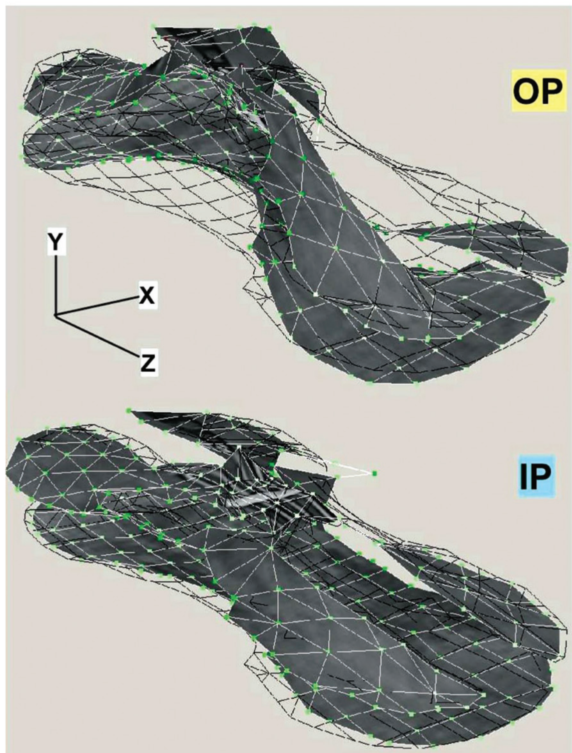


Figure 29. Out-of-plane (OP) and in-plane (IP) motions for a strong corpus mode at 383 Hz for the Plowden *Guarneri* del Gesù *violin. OP motions show a nodal line structure on top and back, while the IP motions show shear-like motion between top and back (same scale for both). Both OP and IP corpus motions imply little net radiation.*

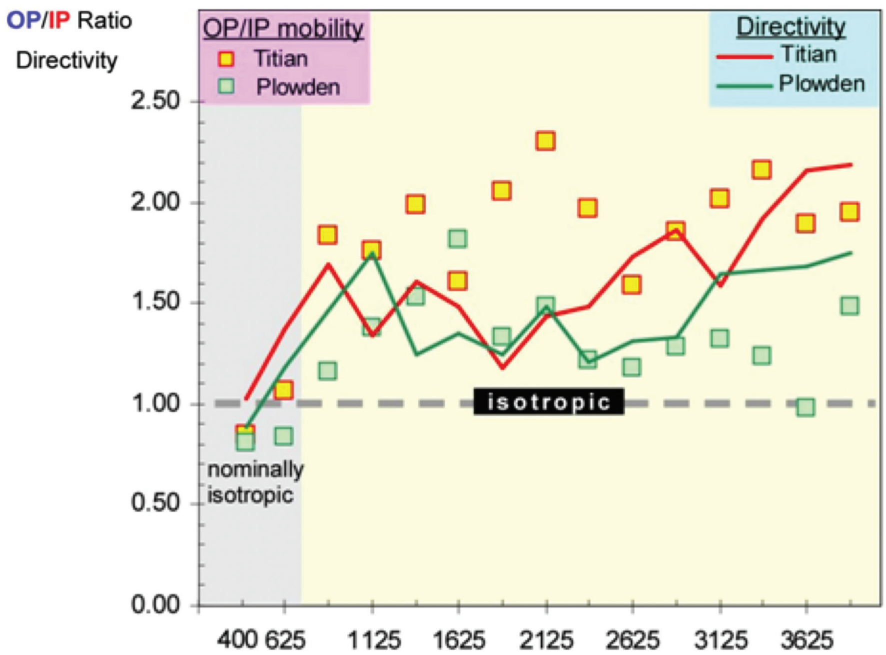


Figure 30. Ratio of out-of-plane (OP) to in-plane (IP) mobilities (squares) and directivity (lines) versus frequency measured for the Titian *Stradivari and the* Plowden *Guarneri* del Gesù.

Dr. Bissinger: On the average, over a sphere, they're all the same, basically. They hop up, they go down, but if you were to just look at the average radiativity, they're scattered, some go up and down. They're relatively similar, but when I split it into above versus below, some go above and some go below.

Mr. Sacilotto: Would a higher arching scatter the sound in more varied directions than the flatter?

Dr. Bissinger: It radiates pretty much the same in all directions. The directive ones radiate off the top plate preferentially. The directivity is almost a factor of two higher for the *Titian* versus the *Willemotte* Stradivari. Also, notice that when the wavelength is much larger than the physical size of the instrument, it's pretty much omnidirectional. So it's much the same radiation in all directions. The thing that sticks out about the *Titian* is that it is directional at the lower frequencies in a region where the wavelength is about the size of the violin. Radiation from the *f*-holes is much more directional than body radiation at the lower frequencies, as you might guess, because it's coming from the top, the air motion in the *f*-holes. At high frequencies, it doesn't get around to the back very well. And so it's going over the top more. This is one of the interesting things that we couldn't measure, but that may be why the *Titian* is so directive at low frequencies, where most instruments aren't very directive.

Mr. Sacilotto: Another question concerns the actual opening of the *f*-holes relative to the volume of the inside of the violin. Could that be measured exactly and what would be the effect of changing the size of the *f*-holes minutely?

Mr. Tao: It would also change the frequency of those lower sounds.

Dr. Bissinger: When I built my house, for the heating ducts I had the choice of small ducts or larger area ducts and larger registers. Now, your fan has a capacity of pushing air at so many cubic feet per minute. For a small pipe, it's got to go really fast to give you that volume flow rate, in cubic feet per minute, out in your room. If you enlarge the pipe, you get the same flow rate, but the air is moving slower. If you enlarge the *f*-holes you're just going to move the air out slower, so it probably isn't going to radiate as much. Smaller *f*-holes may actually be better radiators than somewhat larger ones. That's a tough question to answer based on what we've measured. Long and thin *f*-holes or shorter wider designs may well have a significant effect on the sound, not just be an artistic device.

I have plotted a number of my parameters versus assessed quality of the violin. One of those is total damping versus violin quality, with quality along the horizontal axis (Fig. 31). Note that some of the bad violins have the same kind of damping as the really good ones. Identifying trends is tough, because even among the very good violins, the numbers aren't predictable—the *Titian* is up here, the *Plowden* is down there, or something like that. They keep hopping up and down and crisscrossing. I don't see any major trends.

The critical frequency may be significant (Fig. 32). The two best violins, the *Plowden* and the *Titian,* had the lowest critical frequencies I've measured. The bad instruments, on the average, had the highest. Using Dünnwald's designation identification of a harsh region for frequencies above 4.2 kHz, you can see that the average critical frequency for these bad instruments is up in the harsh region. That's where their peak radiation is. Whereas down around 3.5 kHz is where these Old Italian violins have their critical frequency and you can see it go up and then down. Between the bridge and the critical frequency, and putting those two filters together, you can manipulate the instrument response to strengthen it or weaken it in various areas. We need systematic experiments to be able to make this a systematic procedure—something in the future that we're going to want to do.

Here's a summary plot that shows 14 modern violins as these little lozenges (Fig. 33). The good violins from my VIOCADEAS database are on a green line, and the bad violins are the black line. The rectangles are for the two violins made by Joe Curtin and Sam Zygmuntowicz, and the blue spots are for the three Old Italian violins.

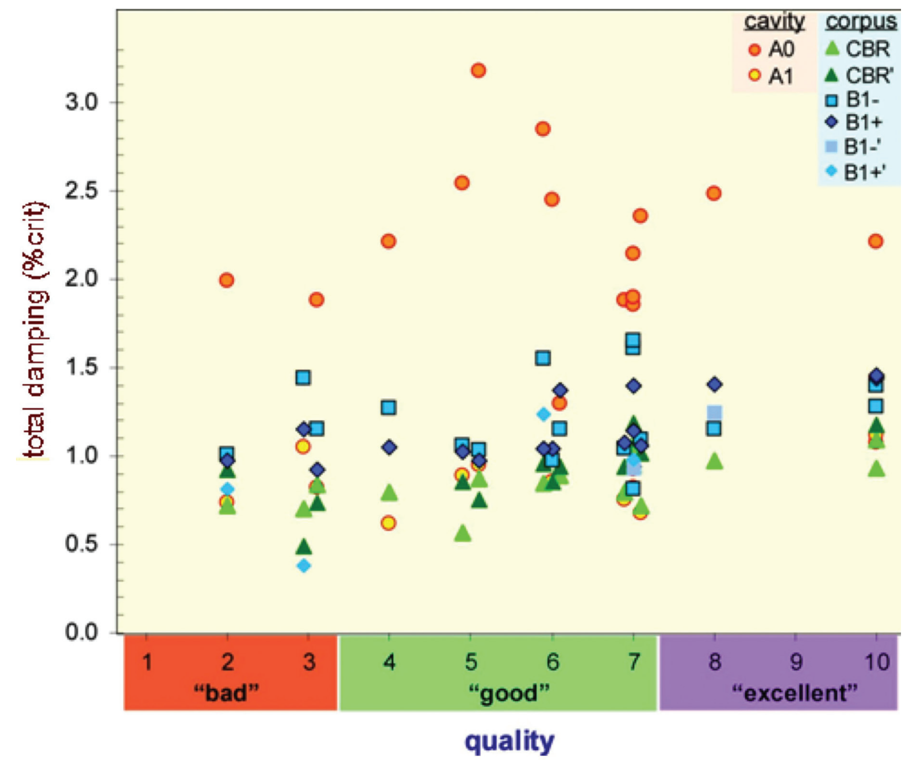


Figure 31. Signature mode total damping (cavity modes: O; corpus: CBR △, B1⁻ (squares, open or filled), B1⁺ (◇, open or filled) versus individual quality ratings of violins. (Primes, e.g., CBR', indicate coupling seen for some violins with small substructure like tailpiece that splits corpus mode into two components.) A0 always had highest damping of any mode; B1 modes had highest damping of any corpus mode.

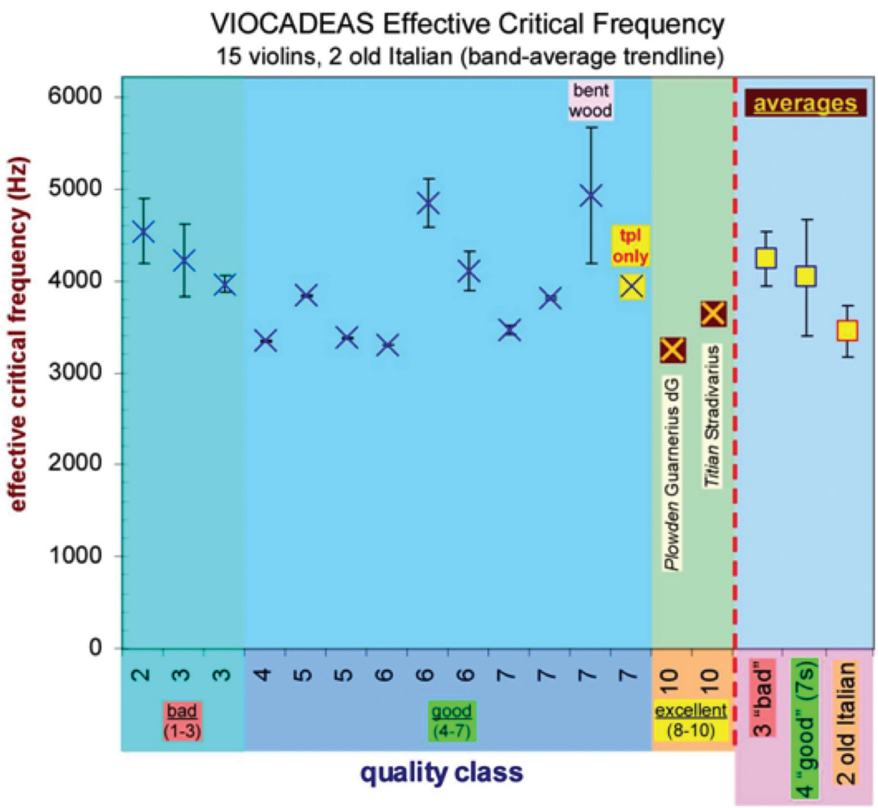


Figure 32. Effective critical frequency (determined from solving three different radiation efficiency trendlines for R_{eff} *= 1; error bars indicate the range of solutions) versus assessed quality ratings for 15 violins, including two Old Italians (*Titian *Stradivari,* Plowden *Guarneri* del Gesù*). (Caution: tpl-only violin had no back plate mobility measurements.) Bad vs. Old-Italian difference in average effective critical frequency is evident.*

Everything should be considered relatively when you talk about quality. If you don't include bad violins in your measurement program, you're never going to find out what beautiful is unless you know what ugly is. So consider the comparatively ugly instruments on the black curve. Notice that in the nasal region these have a relative peak, but in the bright clear region, on the average, they're doing every bit as well as the rest. At the A0 peak, that lowest frequency mode, you can see that bad instruments are really down compared to the good ones.

Some of this is not new. Dünnwald reported this from the systematic scans quite a while ago. Then you look at the Old Italian instruments and see that the strong A0 mode drops down here, pretty much right around where the bad ones are. In that nasal region, it's relatively low, but not zero. That's a crucial point. What's a voice without some nasality? You have to have some of that for character.

Then you go up to the bright clear region and notice how peaky the radiativity for the bad instruments is. The better instruments tend to be somewhat less peaky, and the really good ones tend to have even smoother response and don't push harmonics up just in a very narrow frequency region. If you were in the loudspeaker world, you would not want a loudspeaker with a response peak like the bad violins. If somebody hit that note with those harmonics, they'd jump right out of the woodwork. What you want is something with a nice characteristic sound, but you don't want a huge emphasis.

The sound spectra for the Old Italian violins that Dünnwald published had a nice falloff up here. Now, only for these Old Italians did we go up above 4 kHz, because my microphone calibrations aren't as good above 4 kHz. But you can see they're falling off here. Notice that the violins by Joe and Sam are up in here, and these are average numbers between these two violins.

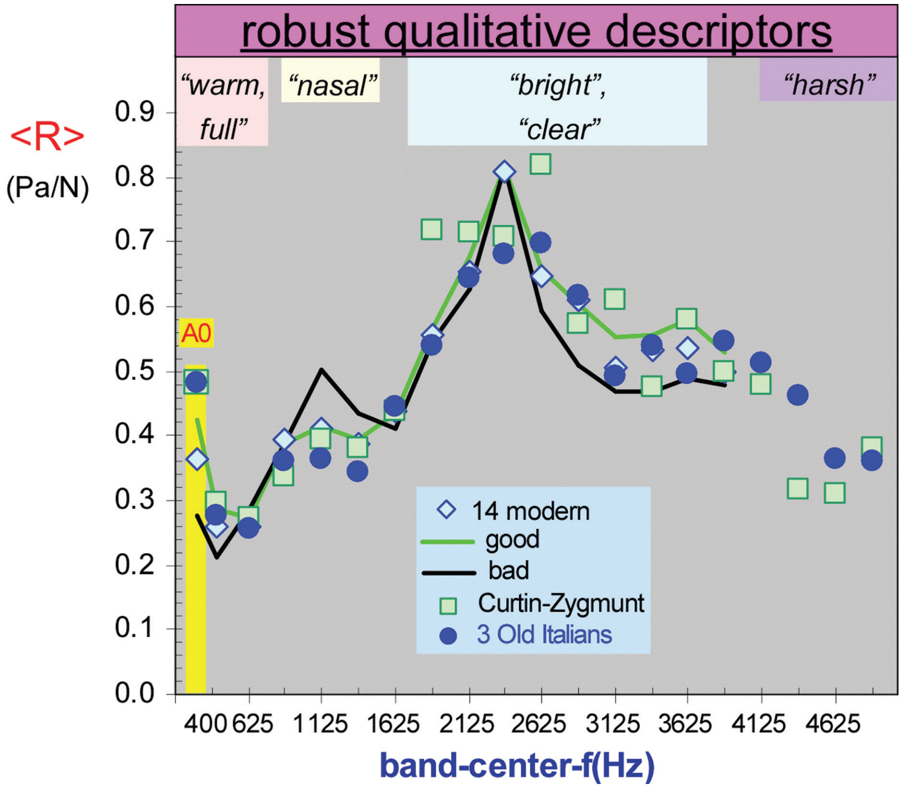


Figure 33. Comparison of radiativity "profile" versus frequency for 14 modern (◇; quality range bad to good) and three Old Italian violins (●; Plowden *Guarneri* del Gesù, Titian, *and* Willemotte *Stradivaris). Also shown are separate profiles for bad (—) and good (—) violins plus the average of two violins from two well-known modern makers (green squares). (The prominent peak near 2.3 kHz is labeled variously body hill, bridge hill, or BH.)*

Notice how broad this region is in theirs. That's a good sign, to not have spiky little responses, but instead a fairly broad, strong spectrum across that region.

Let's talk about materials. You've probably seen a lot of CT scans, like those shown by Sam in Fig. 3. The crucial things we get from the CT scans are the violin shape, which we can create with software, and the density information. Those properties are fixed in the solid model and we can't change them. The things that we can change are the stiffness properties, but we don't know what those are. So how do you find out about stiffness? That's the thing we'll end up with.

Here's a density profile for the top plates taken from the CT scans (Fig. 34). I just did it for 30- or 40-mm steps. You can see that there may be a little bit of glue at the end block because the density is going up. That's a typical place where you slop the glue on. So the density numbers may not be a good indication of what it is. This is in the middle of the plate, not on the top, not on the bottom.

Look at this density here for the *Plowden*. It's quite low. And then up here it really hops up. Well, there's patchwork around the bridge that includes new wood and glue. These models can incorporate that detail. If you think that's a good violin, nobody really cares whether it's high there.

Mr. Tao: Were you able to take a pixel within the patch or in the wood that rests over the patch?

Dr. Bissinger: No. I took a block of ~30 pixels and did an average. So you're seeing good wood, bad wood, glue, everything. We're now in a world where specific, detailed densities are not very important because our wavelengths are large compared to pixel size. So it's not a big deal. But these trends are important for the models to incorporate, because the CT scan that they're based on has a hump right in there. At the other end, near the tailpiece, the density is low. It appears that the *Plowden* probably has a top plate of spruce of lower density than is typical.

Now, I put in here nine good modern violins, not bad violins, because I don't think they chose the wood very well for those. For these good violins made by reputable makers, there's the range. From Dan Haines's wood table, I took the maximum and minimum values of density. He includes density data for European spruce and a number of subspecies, but their average densities overlapped. So I took the maximum and minimum values to define the range of densities. The density of the spruce top of the *Plowden* falls a little bit below that range. The *Titian* spruce top density pretty much falls below too. But the density of the *Willemotte* top looks like it's a little bit higher typically across. That's the kind of detail you can get. And this is just one little stripe down the center. You can then go left and right. The density profile for the back plates may be more interesting (Fig. 35). Included are nine good modern violins that were tested in our VIOCADEAS project. There are Haines's results in the gray there, and you can see that the *Plowden* back plate density is really down here. So it's the same kind of average, just slice by slice.

Mr. Tao: It is interesting to look at Jeff Loen's thickness maps afterwards because the *Plowden* is quite thick in the middle of the back, and generally rather thick. Judging from these density numbers, however, it's back might not weigh any more than the *Titian* back.

Dr. Bissinger: That's right. Both the *Willemotte* and the *Titian* are right at the fringe area here. So it looks like these could have lower density. Here are the Haines density numbers for spruce (Fig. 36). Going crosswise towards the in-curves on the C-bouts, for example, and the maximum widths in the upper and lower bouts, it's pretty much significantly below. It appears that the density, as you go from the midpoint here, on the two sides, is not necessarily symmetric. You can see that it's higher on this side, and then it drops down and comes back up. This is the lower bout here in the green. There is the upper bout, and that pattern is pretty regular across. The difference in maple density for the two sides can be fairly substantial, as it is for the *Willemotte* Stradivari.

These CT scans give you so much information about density that you're going to be totally overwhelmed. I'm not sure whether you want

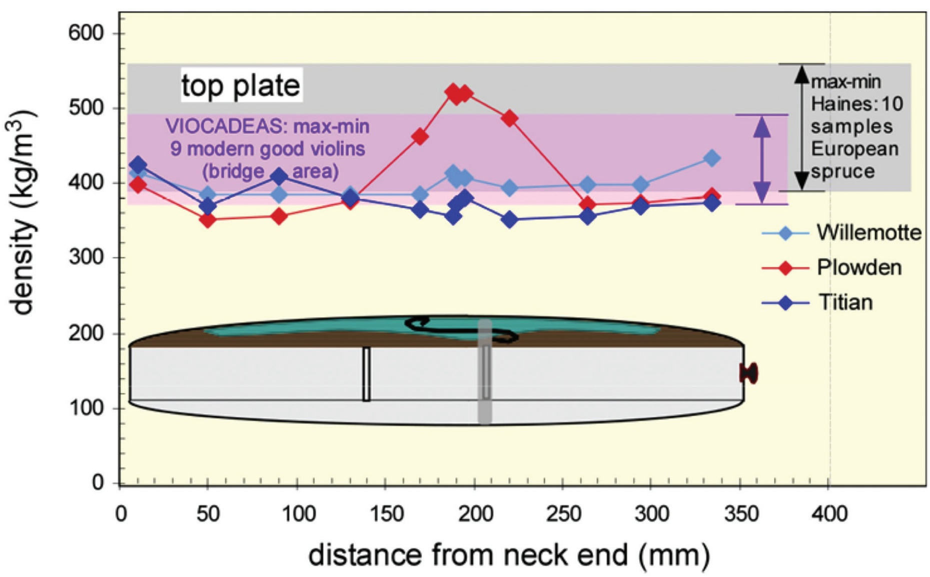


Figure 34. Measured density profiles extracted from CT scans along the length (arch ridge) of the spruce violin plates of the three Old Italian violins. Shown for comparison are the range of spruce densities for nine good modern violins and the Haines listing of 10 samples of European spruce. Note the density rise in the bridge area for the Plowden *in the region with some repair work.*

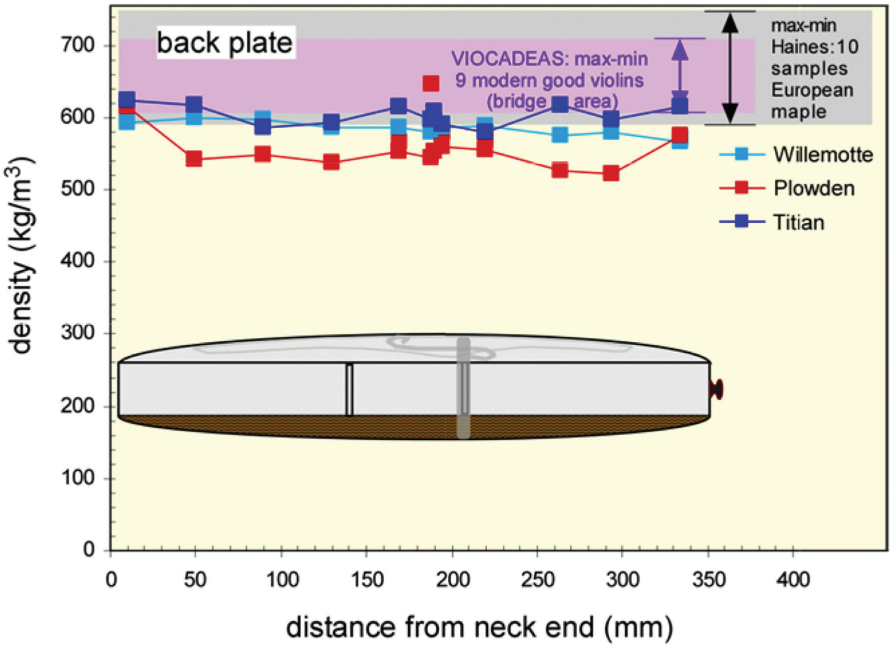


Figure 35. Measured density profiles extracted from CT scans along the length (arch ridge) of the maple back plates of the three Old Italian violins. Shown for comparison are the range of maple densities for nine good modern violins and the Haines listing of 10 samples of European maple.

to go pixel by pixel on these things, or whether you just want to work in 10 x 20 pixel blocks. I don't understand everything in it myself, but the important thing for a violinmaker—central to everything we do, all of our dynamics, all of our esthetics, our CT scans, our simulations—is proper knowledge of the materials. If you don't know your materials, you can't do this well. We're trying to understand materials because it's central to everything that we can measure on a violin.

Let's end up with comments on stiffness. We have a spring with a mass on the bottom. You pull the mass down, release it, and it goes into oscillation. We can compute the frequency because there's a simple equation to do that. Suppose we change the problem. We know the math and we know the frequency. Can we work out the stiffness? The answer is yes. We use the same equation reorganized to isolate the stiffness.

I've told you that the frequencies of vibration for these Old Italian violins aren't remarkable, and the densities, while a little bit lower, are not incredibly low. I'll argue that the stiffness of this wood also cannot be remarkably different. It's going to be somewhat different because it's 300-year-old wood versus 100-year, or 50-year, or 25-year-old wood.

Our solid model knows nothing about whether you dumped your plates into peach brandy and hung them out in the sun for a couple of months like one maker I heard of. He said this was the secret to Old Italian sound. Or whether or not you do water glass or any wood treatment, we can't know. All we measure are some stiffness and density parameters. So, to make duplicate copies of these old instruments, by the time you do your treatment and your varnishing, you also will have to duplicate those stiffness and density numbers. Then you should get the same mode frequencies. That's going to be difficult to do because varnishing and treating the wood changes things. We're looking at the end product and giving you the end values for this. So that's what you have to aim for, not the initial values that you've got.

What can a solid model do? In combination, it can do things that the experiment can't do. Of course, the experiment can do things that the solid model can't do. Have you ever been able to make your plates thicker, or have you been able to increase or decrease the arch after you carved out your plate and finished it? Or refigured your bassbar, changed your wood properties? Sup-

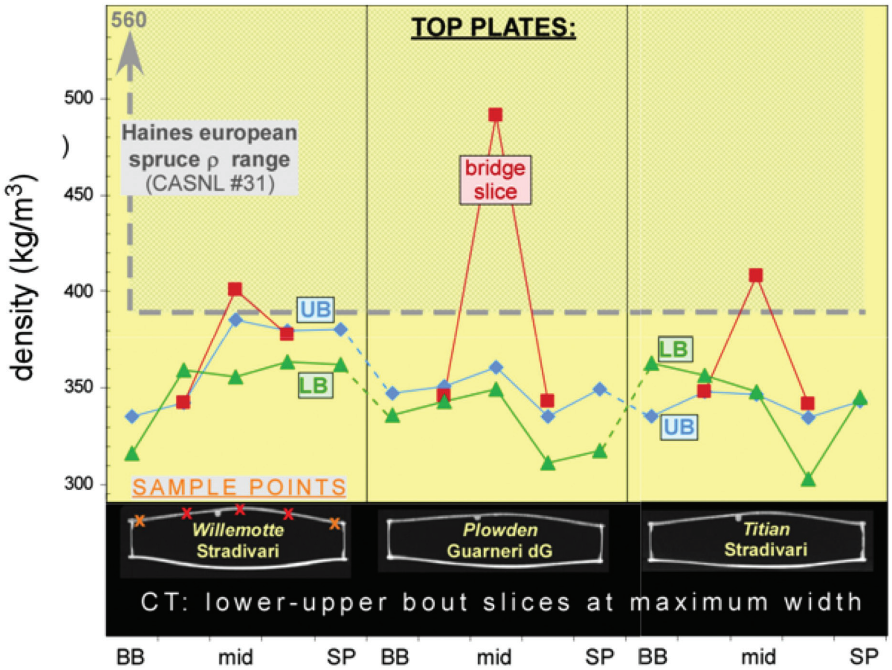


Figure 36. Measured density profiles extracted from CT scans across the upper (blue diamonds) and lower (▲) bouts and the bridge plane of the C-bout (red squares) of the spruce top plates of the three Old Italian violins. The Haines listing for European spruce is indicated as a reference. Note the density rise in the bridge points in the regions with some repair work.

pose you think, "I don't like this piece of wood, so I'm going to use a new piece of wood." What's going to happen? This is where the solid model is super. With your wood properties known well, you're free to change your geometry. You can do anything that you want to the geometry, keeping the same wood. And that gets rid of one of the variables that kills us when we make measurements, because it's always for this particular violin, and then it's this other violin. We can never do anything like that on a regular violin, unless we do something like Martin Schleske did with systematic thinning of the plates. Of course, the experiment can do things that the solid model can't do, like measure actual damping and the response to forces at the bridge whether the violin is free-free or held.

Mr. Tao: Are people clear about what George means by a solid model? It is a computerized simulation of a violin where you can change specific attributes one at a time. You can ask, what would happen if I lower the arch by 1 mm? It can make that change and then tell you what the effects on vibration will be. With the data he has collected during the 3-D experiments plus the geometry from the CT scans, George is saying you can model a virtual violin that you can then alter at will.

Dr. Bissinger: Right. At Oberlin College last summer, John Waddle brought along some prototype Old Italian violins in plastic which had been recreated from CT scans. They were very accurate three-dimensional models, inside and out, including the soundposts, that you could have sawed in half to take a look inside.

John Waddle: I've got them here, George.

Dr. Bissinger: Then please show them to those interested, because that's our solid model, except it's expressed in mathematical terms in the computer to be able to do the calculations. It's created from CT scans with that shape and density information, and with special mathematical procedures to have the computer understand the shape, densities, and the stiffness.

Mr. Tao: Oliver Rodgers did some of the very early work on this by completely constructing it theoretically of finite elements. That means limiting the number of factors so that you can vary them on models of violins. He published papers about this topic in the *Catgut Acoustical Society Journal*. They're very simple compared to what George is talking about doing, but years ago they overloaded the University of Delaware's computers.

Dr. Bissinger: Yes, he did computations for plates and bridges. There is some very interesting material in Oliver's old papers about influence diagrams. If you shave off the wood here, what does it do to the plate modes? Martin Schleske has said that plate mode frequencies don't count all that much. Well, maybe he likes to manipulate them in the glued-together product.

WHAT DOES IT MEAN?

Mr. Tao: What did we actually learn from this study?

Dr. Bissinger: Although I don't think that any maker will have understood all of the details presented here, every maker can work in a systematic way, keeping records of what he/she does. Maybe once a month you can pull a piece of wood aside and do something in a systematic fashion to it, measure it as you proceed, and try to understand what happens. Whether it's a substructure like a plate or it's an assembled instrument, you can play around a bit.

Mr. Tao: So you're actually describing a process.

Dr. Bissinger: That's right. This is the process we've been doing at Oberlin for some of these experiments. I mentioned the project with bridges: systematic variations of the waist on the bridge to change the rocking mode frequency. We took this very good instrument and made it sound like a student instrument without changing the instrument at all. That tells you right away as a maker that your setup is a crucial part. I've worked with makers my entire career in measurements. I worked with Carleen Hutchins for a while and also with Bob and Deena Spear. I've always been in the practical world where you have to do something to get something. But these systematic measurements have turned out to be much more informative. As did Martin Schleske, for example, and as we did at Oberlin, the experiments were very informative about what's going on. You can look at that radiativity profile up there and you can see the blue curve, it was good. The red curve, it was still good, but the black curve, it was terrible.

If you make measurements in a consistent way, you have a chance to turn them into something you can use for practical purposes. Once you understand the radiativity profile, you have a sense of the sound of that instrument and you can go to various spectral regions like 3 kHz or so, and what do you have there relative to everything else. These are all relative curves. You cannot do anything without doing things relatively, because every experiment is different. If you're interested in doing this, spend some time getting a good setup, and then use it in a consistent manner.

Mr. Tao: I often have discussions with violinmakers about the role of science in violin making. My perspective is that more often than not, there's a misunderstanding of what science actually is. What many violinmakers think of when they think of science are equations and complex measurement apparatus. Those things are only the tools used by scientists. Science is really a process and a methodology. As George is talking about keeping systematic notes to understand the role of variables, you can do science even using very crude, simple tools and do violin making in a very scientific process in that sense. That's really what science is about. It's not necessarily about equations or complex apparatus like this.

Dr. Bissinger: You're right. Science is a search for patterns. Somebody that's built only one violin doesn't have much in the way of a sense of patterns. What will I get if I change this? But after you've built violins for 30 years, you have a very good idea of what you're going to get if you change something.

Physics is the way of taking those patterns and putting them into mathematical form so that you can make predictions: If I change this by a certain amount, I will have this change by X amount. Now, that's the crucial distinction. Most makers do the scientific part in a background mode. They pick up this experience. They've identified patterns. They learn what's going to happen if they do something. What they haven't done is put it in a predictive form, which means Y is equal to MX, like a straight line or something like that. That is a way to say, "If I change it by this amount, that will change by so and so." We're never going to get to a simple equation, but what we're going to be able to say is something like, "If you change that waist by a certain amount, you're going to drop the output in the 3 kHz region by so much." Now, is that good or bad? I don't know. It depends how high it is. But there's the basic concept.

Mr. Tao: I would like to return to the question: What did we learn from this particular project?

Dr. Bissinger: We've learned that you can make a solid model from CT scans. This is a true solid model built directly from those CT scans, so we can now create the geometry of any violin quite accurately. If you have enough money, you can buy this. This is what the computer understands, that shape. If we modify certain parts of the violin, like the bridge, in certain ways, we also can look at these patterns of curves and see things change. We've also seen that there are simplicities in terms of the bridge and the critical frequency that makers can affect by varying the physical geometry, density, and elastic modulate properties of the materials they use. These are all things that affect the sound. Rather than an experiential world, where I know the sound will get brighter if I do this, or something like that, we look at it a different way, such as where in that frequency spectrum will we be able to affect things?

The sense I'd like to leave with you is that the violin is a complex object—it's never going to get simple, but there are physical simplicities about certain aspects of the violin makers can adopt and then put into the way they build one. And as the generations go by, that will become part of the knowledge of makers.

Mr. Zygmuntowicz: The answer to the question of what we have learned is more complicated than we like, but I there are a few things to consider. First of all, George has just begun to crunch numbers on this, and you should stay tuned because the real meat of his research will be emerging over time. Performing hard science takes time and real expertise. But there is another kind of science, as Fan was talking about, which is experiential science. This requires using a more analytical approach to what we do.

I was curious about acoustics and acoustic techniques for a long time. I would talk to Norman Pickering at various events and I even went to visit him. I had questions about the meaning of such and such and I never seemed to get answers that were really satisfying, but not because the scientists didn't know the answers. As an example, there was a Federation meeting a few years ago where Erik Jansson was speaking about the violin bridge. One of the guys in the audience asked, "Does this mean we should make our bridges thinner?" Jansson smiled and said, "What you're interested in is different than what I'm interested in." Physicists have very specific questions and they're appropriate. If you want to get answers to your own questions, the only way to do that is to get your hands on the technology yourself, and then you can ask your own questions and fool around with it. That's been my experience, getting involved with the summer VSA Acoustics Workshops. Norman Pickering actually put a Trojan horse into my hands by lending me a piece of his acoustic equipment: a transducer apparatus.

One of the most meaningful things on the *Strad*3D disk is not that it's going to tell you what is different about the old violins included in it. For me what still is the miracle is not what makes a Strad a Strad, but why the violin design is so effective and how the violin actually works. I think that within that disk there are incredible resources to understand more about the violin. You'll find all kinds of tools in there to help you explore that—as little or as much as you want.

With a laptop computer any maker can start to do meaningful work in this field, which wasn't the case a long time ago. We can be thankful for the insightful work of those who have accomplished a lot of the fundamental work, such as George Bissinger, Norman Pickering, Oliver Rodgers, and Carleen Hutchins. So there's been a huge demonstration of technology, and now it really is accessible to any of us in a way. We can't do what George does, but he doesn't do what we do. We have our own sometimes-simple questions, and I think there is considerable ability to get deeper into it now with this sort of stuff. It can appear daunting until you get your hands on it yourself. So, I hope that you will start fooling with the controls. You'd be surprised what you can do.

Dr. Regh: I think one of the things that we overlook is that we are focusing on the answers. One of the outcomes of a study like this is that we learn to ask much better questions. And when we do, we find much better answers as a result. The typical example is when you're at the starting line of a race and the gun goes off, and you go like hell. However, if it's a marathon, you are not going to win. It's important to have a clear understanding of what you're looking for and the goal before searching for an answer. If nothing else, this study has produced much more intelligence and more focused questions. The answers are going to come, and come faster as a result of this work.

Dr. Bissinger: Let me answer Fan's question another way. Many professional violinists say there's something unique about Old Italian violins. Do these measurements show that there really is? Well, in the generic sense, they don't. One violin behaves like all other violins, including all other violin octet instruments and the cellos I've tested. Every one of them does basically the same kind of thing, which is good news. You're not working with a remarkably different instrument where you have to jump over some mythical bar. You're working with materials and you've got to understand them, but the shape is done pretty well. You just have to start working on the setup of the instrument. The influence of the egress filter is nowhere as strong as the bridge filter, and you can see that right there. And the bridge needs the soundpost. I made measurements with that and I've played a violin without a soundpost, and they're just like night and day. Same bridge, same everything. That's an area that has a major influence, immediately around the bridge. That's where you really have to master it. If I were a maker, I would concentrate on that area. That's where the setup experts concentrate, and they know what they're doing.

Mr. Tao: Let's concentrate on that area. Sam is going to do a little impromptu demonstration.

Mr. Zygmuntowicz: We've been trying to find ways to look at sound, and now we're going to find ways to touch sound. Fan is going to play around on the violin. If you play semi-tones up on the E-string sometimes you get a note that's a little duller, and then you hit something dramatically different. So, something hot is happening on that note. So the question is, what is the simplest modal analysis tool that there is?

You can do this very simply. When you play a scale, sometimes there is one note that is really edgy. If you can measure the spectrum of the sound from that violin, you could identify what frequencies are disturbing you. You need some kind of spectral analysis software, of which there are many. The SpectraPlus™ software is excellent, although it's a bit expensive. There's simpler stuff. If I am trying to troubleshoot a note now, I first decide which area is disturbing me, and then I measure the radiation spectrum. Hopefully, it might be evident that there are a few spikes on the violin that I can identify.

For example, let's say that there was a really disturbing couple of spikes around 4,500 Hz. Using Oliver Rodgers' modal sniffer, which is basically a little microphone with a signal generator, I could hunt around on that violin, or I could do it with my fingers as well. If I didn't like the sound that was coming from a particular area, I might trim the *f*-holes a little more to bring it higher. I could weight the *f*-hole down, or I could put a stud in there to change it. You're going to shift it from one place to another place. It's a very complex system, so it's not so simple. Recently, on a violin I was working on, there was a big spike at ~5 kHz. I was able to locate and dampen the hotspot a little bit, which did make the violin behave a little better without affecting the rest of it too much.

The dream of all this is like doing genetic testing instead of just looking at someone and saying, your color is not good. You can actually identify the frequencies that are troublesome and where they're happening. Then you can change a single frequency or single aspect of damping behavior or bands of behavior. I don't have my computer on my desk, but having seen all that, I know that I want more motion for my low modes and I want more localized stiffness for my high modes.

I'm thinking about the way things move

and the way arching works. This is not new. I showed a violin of mine that was troubling me to René Morel, and he said that the arching was too curved right under the *f*-hole, it's stiffening up the whole top. Well, I didn't think about it that way before, but once you see the way things bend, you put a little more arching and it's going to bend less across the arching.

Without understanding very complicated things like critical frequency and damping, you can understand structural things about modal behavior, about what particular motion is causing what particular frequency and how that contributes to the sound of the violin. I expect that you all have had the experience of one of your clients playing your instruments and commenting that, while it sounds pretty good, why is it so "screamy" right here? You might adjust the soundpost for half an hour, and they go away, but they're not really happier and neither are you. There's a limit to what we can do using traditional techniques. Acoustical experiments are an expensive luxury, but I think the quality of and demand for modern instruments has risen enough that the bar has gotten higher. If you want to meet the new bar, you have to find new ways to address that. The more accomplished your clientele, the more difficult it is to do so. So I'm not doing this for fun, although it is fun. I'm trying to aim for a bar that keeps getting higher. As everyone else's work gets better, I've got to keep mine there too. I think that has become a dilemma for the modern maker—to meet standards that may be impossibly high.