REPORT ON A BASS BAR STUDY

Thomas Croen and William Atwood

Monday, November 11, 1996, 1:30 pm

Albert Mell: For the next presentation we have two people, one who is a violin maker and the other a scientist who makes violins as a hobby. They share a passion for the violin family, which is what brings us together today. It's not a question of whether we are makers, players, collectors, or whatever; we are all what I like to call violin buffs. We are enthusiastic about the instrument, we love the instrument, and we'll do everything to help perpetuate it. That has been the real aim of the Violin Society of America from its very beginning, and it explains why we meet and why we have such a diverse membership.

Not only are we diverse but we are very open. People who have come here from Europe are accustomed to guilds. Guilds, as you know, are usually secret organizations designed to restrict their activity to a very special group which more or less maintains control of their craft. Europeans find it remarkable that we are so open, so willing to share our information. That has always been one of the goals of the Society. We hope to continue that procedure.

I first met Bill Atwood in Oakland. I had never seen him before and somehow or other we struck up a conversation. There I was, an amateur violin maker and editor of the Society's *Journal,* and he mistook me for a professor of English. I finally disabused him of that yesterday. I wasn't a professor of English, I was a violinist, I was a musicologist, and a professor emeritus of music at Queens College in Flushing, New York, and I founded and edited the *Journal.* What is interesting, however, is that here we were, two very different people, and we struck up this very close bond of friendship.

Then I did something dreadful: I introduced Bill to Tom

Croen. That established another relationship, and the two of them have been working together, the man who is a scientist who comes to violin making as a hobby, and the man who is a professional maker, both of whom love the violin. I am sure they are going to have some interesting things to say about a subject that has been very controversial at our meetings: bass bars.

The controversy begins with whether we spell bass bar as one or two words. From there, the questions arise: Do we spring the bar or do we not spring the bar? Is it just a structural element or does it have acoustical reasons for its existence or is it both? Why don't we put it across the instrument rather than along the length of the instrument? This was a very serious discussion not so long ago. So we hope today to resolve all of these problems and I am sure that Tom and Bill will be willing to answer all your questions. Bill Atwood and Tom Croen.

Tom Croen: Thank you, Albert. Bill and I engaged in a discussion last summer, and this project—in which we examined bass bar tension—is what came of it. Tension, or spring, is created when the curve of the bar is of a smaller radius than the curve of the top. When the bar is clamped into position at the center, there is a gentle rise away from the top so that, when glued together, some pressure is required to pull the two together. We asked ourselves: How could we find out if tension has an effect on the sound of the instrument and does it affect the top's ability to resist the pressure of the strings?

I'm going to begin this session with a historical perspective, and then go through the process of installing a bass bar, showing some slides. Then Bill will talk about how we set up the experiment and our observations. Since this discussion is about tension, we are not going to go into detail about tuning or shaping the bar.

A Brief History of Bass Bar Tension

In researching this subject, the earliest reference I found to tension came from the book *Rules for the Construction of Violins, Violas, Cellos, and Double Basses* by Antonio Bagatella, written in Padua in 1782. Under the heading "Observations on the use of the above mentioned rules" we find:

> On the side of the fourth string, as everybody knows, a bass bar is placed, and it should be equidistant from the center, both above and below, and placed in a straight line. The middle of the bass bar should fall exactly at the *f*-hole nicks where the bridge is placed. It mustn't be too big and it should be placed inside the upper eye of the *f* hole little more than a quarter of one of the intervals. Its length is to measure thirty-six intervals, and no longer, and it is to

> be placed in a way that it pushes upwards so that it can reinforce the belly and prevent it from caving in. If it were to be fitted without tension, the force of the strings would cause the table to deform.[1]

I found another reference from a book of letters and memoirs of Count Ignazio Alessandro Cozio di Salabue, translated by Andrew Dipper and David Woodrow, entitled *Technical Studies in the Arts of Musical Instrument Making*. Under the heading "Catene, Bass Bar—the manner of placement":

> The Amatis and Stradivari commonly placed them half a ligne from the *ff* at the center; then the lower portion of the bar is placed half as much further away from the center line than is the upper portion. All the same I must warn you to keep it plumb to the plane and not at right angles to the table, and to place it close to the eye of the *ff* so that it produces more power. When you fix it in place there is no need to make it pull (spring) the belly so much that it takes a greater curve than necessary and so produces a dry tone through impeding the vibrations, but only slightly. In order to make bass bars that vibrate more and do not play false, they have to be chosen and placed in accord with their grain and made from wood that is lively (spirited).[2]

I also spoke with Bill Monical, who works in New York and has studied and worked on many instruments in their original condition. He described instruments from the mid-1700s containing things like strips of linen, approximately 1 cm by 3 cm, stretched over the ends of bass bars like band aids, or a bead of glue running the length of the bar with a large deposit on the ends of the bar. There is anecdotal evidence that these makers were concerned that their bars might come loose if not reinforced. It was also common to see bass bars fit on the slab rather than quartered, sometimes narrow and tall, or short in length and stoutly shaped.

In a discussion I had with Vahakn Nigogosian, I learned that in France in the early part of this century, there were some makers who fit their bars with 4 mm of tension on each end, but then carved the upper silhouette of the bar to near-finished dimensions before gluing it in place, which would certainly diminish the actual amount of tension.

The next reference I found is from Hans Weisshaar and Margaret Shipman's book *Violin Restoration: A Manual for Violin Makers*, which is, in my opinion, the best resource that details procedures for doing first-class repairs. In the section on bass bars, they make these spirited remarks:

> There are many advocates of fitting the bass bar onto the table with tension. The question is, how much? We see no advantage in fitting the bar with tension and believe that this practice can be detrimental to the instrument. Excessive tension invariably pulls the table

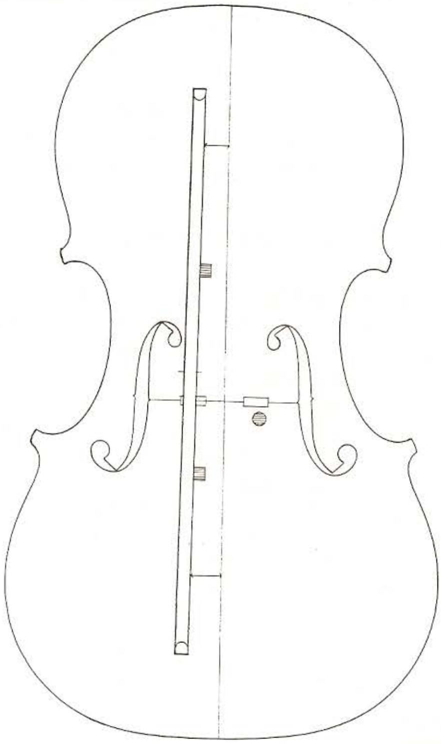

Figure 1. The position of the bass bar relative to the center line, and the two locating cleats.

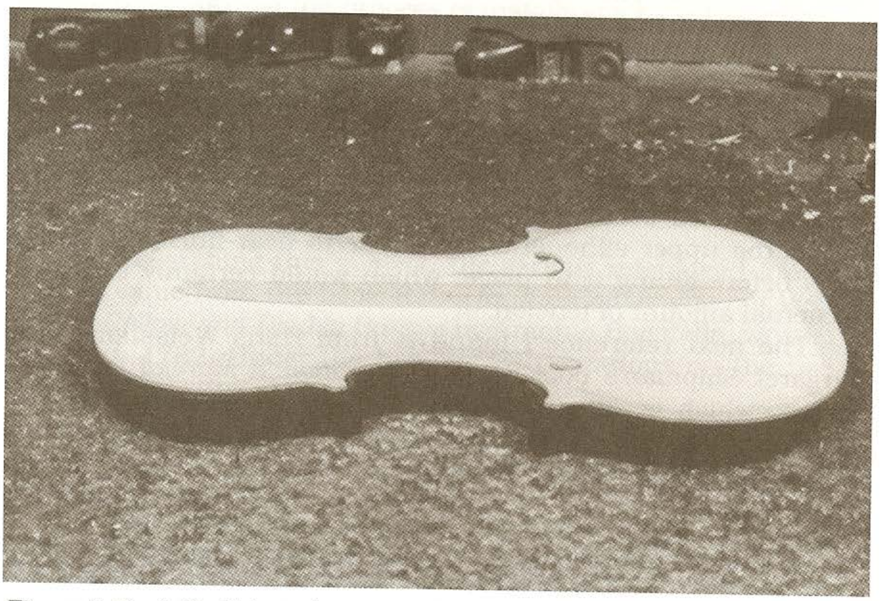

Figure 2. Partially fit bass bar; the line going the length of the bar is the split line.

> arching out of its natural form because the mass of the bar will cause the table to conform to the bar's arch, not vice versa. The "tension" theory might well have been invented by someone who did not know how to fit a bar without tension! An equally strange theory holds that a sunken arching in the bridge area can be raised by fitting a bar with tension![3]

In my opinion, it is the problem of arch deformation which has led many to be suspect of the idea of using tension at all. After all, if there is sure to be damage, who wouldn't be suspect? But, in fact, there are ways to distribute the tension in a bar and not have any distortion. In the following section I'll describe how to achieve this.

It was very important for our experiment to have a method that would give us reproducible results. So we designed an experiment in which we took one violin and installed three successive bass bars, each cut from the same piece of wood. They were positioned and carved identically, with the only change being the different amounts of tension. And then we measured everything we could think of (like the bear going over the mountain) to see what we could see.

Procedure for Bass Bar Installation and Shaping

When selecting and preparing the wood, I like to use lightweight, strong wood with narrow grain, perfectly quartered and split. I then prepare it to 5.5 mm thick by 15 mm in height.

First I establish the angle of the length of the bar by dividing the width of the plate at the widest parts of the upper and lower bouts by 14 and then go out one unit from the center line (Figure 1). What happens if you use a different formula? If you divide by a smaller number like 12, it will become *less* parallel to the center line; a larger number like 20 will become *more* parallel to the center line. Determine the length by marking with a compass 40 mm from the ends of the plate and trim the bass bar approximately 2 mm longer on each end; lay the bar in position using these points, check the split and adjust if necessary, then transfer line of arch to bar with a pencil using a finger to guide, and then cut it out on a bandsaw (Figure 2).

I use a large, flat finger plane (60 mm) for approximately fitting the bar. When the vertical angle is good and the fit is close, clamp it into position at the ends. After checking the position relative to the bridge with the bridge in position (Figure 3), I also check the lengthwise angle and vertical angle again. When satisfied with the adjustments, glue two cleats to the top on the center (downhill) side of the bar as shown in Figure 1. The rest is easy.

The final fitting is done with chalk, used sparingly so it

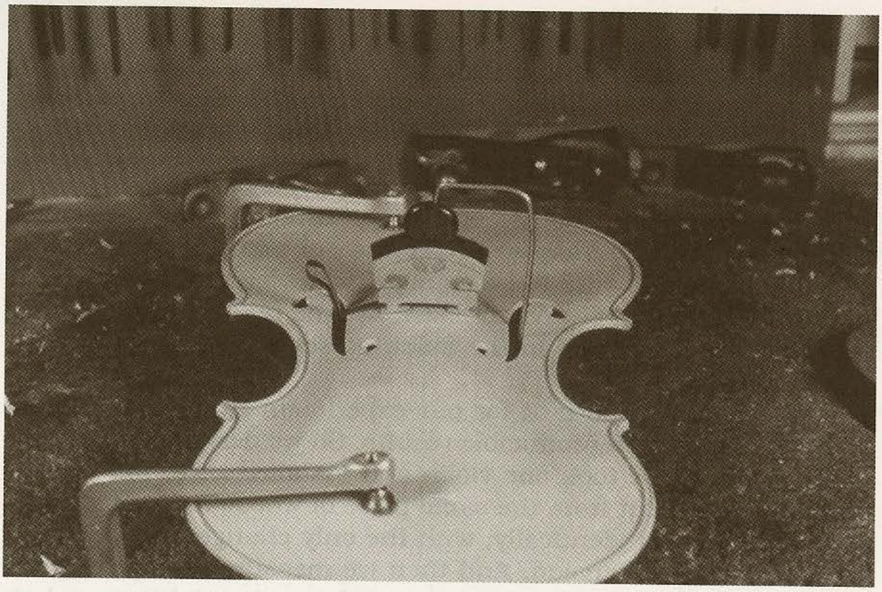

Figure 3. Clamps holding the bar in place at the ends. Checking the bass bar placement relative to the bridge with the bridge in position.

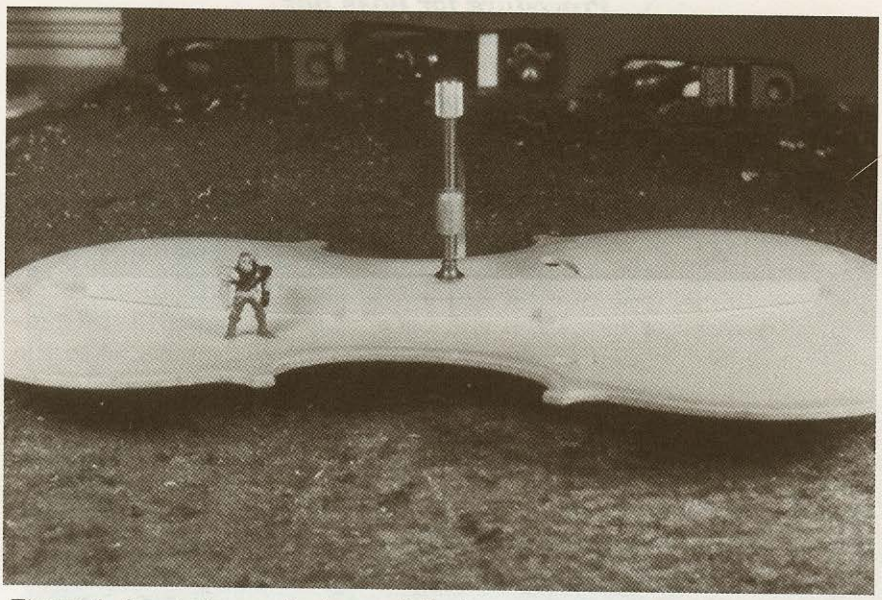

Figure 4. Gap between the top and the bar; note the moderate use of chalk, the cleats, and the essential apprentice.

ecking the bass
sition.

ate use of

doesn't build up. Any sideways rocking or twist needs to be removed whenever it occurs, before moving on with the fitting of the bar. I still use the same flat finger plane for fitting, occasionally employing a file with controlled lengthwise strokes. This helps to smooth out any roughness that may be there, but if you overdo it, you'll round off the edges of the bar.

Arch distortion related to tension usually appears in the form of a bulge on the outside of the top and occurs when the bar rolls all the way out to the ends. I prefer a method of installing a bar with most of the rolling in the center half of the bar, so that when it is rocking in position it nearly makes simultaneous contact in the outer quarters, and when glued into place there isn't any arch distortion (Figure 4). This focuses the support in the center where it is needed most. During my research, I spoke with Carl Becker about this. He told me that his method of tension distribution also makes for a very gentle fit in the last inch or so of the bar.

Gluing the bar is another procedure in which deformation in the arch can occur, which is why I set up a dry run (Figure 5). I use a rib on the outside to protect the arch. Then I arrange the clamps and mark their position on the top of the bar. Next I start warming the top and bar using a heat lamp. While the glue is warming up, I like to clear off my bench and arrange the clamps in a way so that I know where each one goes. It helps to minimize the fussing during gluing. Once the top and bar are warm, I apply the glue to both, going back over the areas where it has soaked in. The first clamp goes on in the center, then I work out toward the ends, while making sure that the bar is straight. This is where those cleats really do their job preventing sliding. The clamps are tightened so that the top and bar are making snug but not tight contact. (Note: The Weisshaar-Shipman book has an excellent section on working with hot glue.) That bulge I mentioned can also be caused by the top soaking up water, so when cleaning up I don't use water. A stick to squeegee the glue and a rag to wipe it off is all that is necessary. Later, once the bar is carved, a slightly damp rag is OK as long as it is not dripping. I usually remove the clamps after a few hours and let it set overnight (Figure 6).

To begin carving the bar, first remove the cleats. To aid in carving the bar I use this template that Charles Rufino told me about (Figure 7). It represents the highest bar I might ever make, and because the bottom of the template is more curved than the top, it will fit anything. Simply lay the template adjacent to the bar and, using a pencil, trace the upper curve onto the bar by rocking the template along the curve, thereby picking up its height. Then trim the bar down to that dimension (Figure 8). Marking the center line of the bar is helpful when carving the

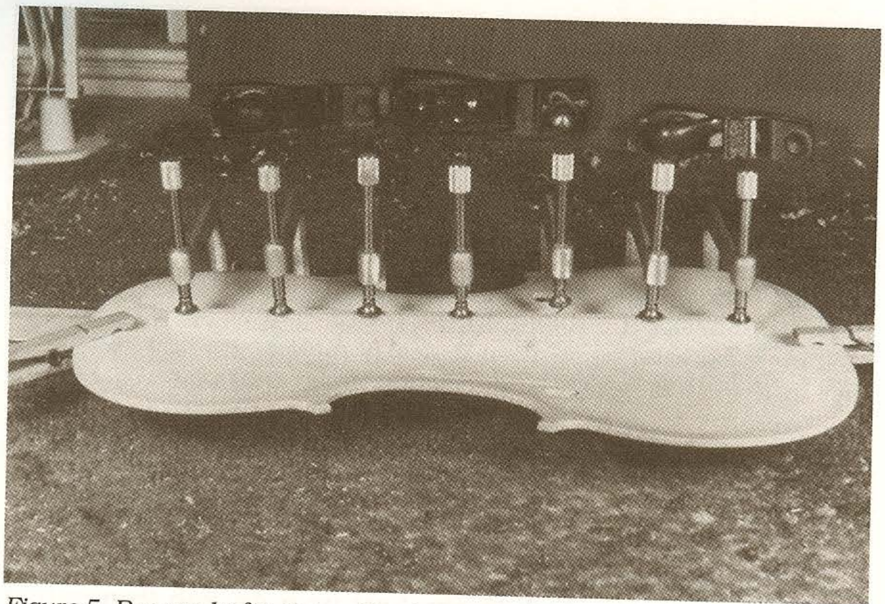

Figure 5. Bar ready for gluing. Top is protected on the outside, clamp position is marked on the top of the bar, and chalk has been removed.

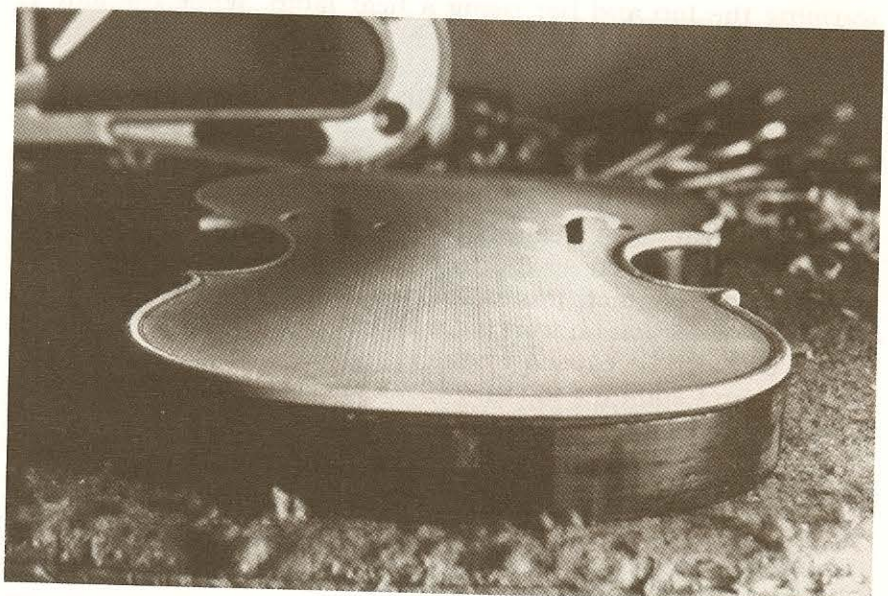

Figure 6. Shows no trace of arch distortion after successfully gluing in a bar with tension.

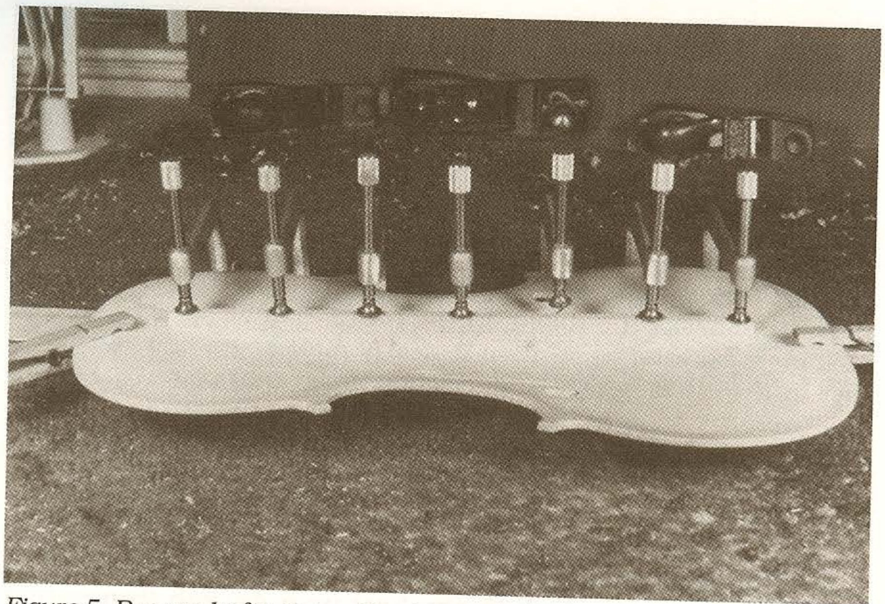

Figure 5. Bar ready for gluing. Top is protected on the outside, clamp position is marked on the top of the bar, and chalk has been removed.

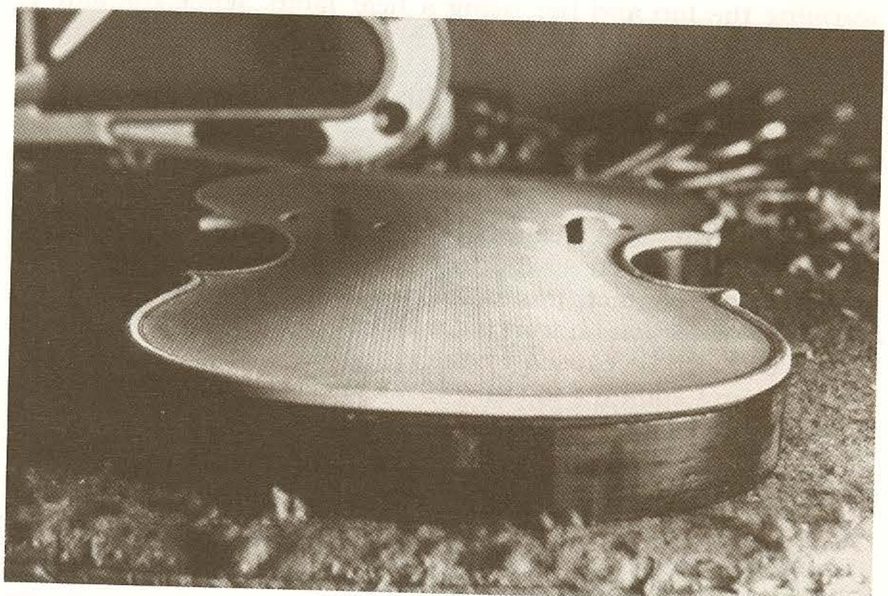

Figure 6. Shows no trace of arch distortion after successfully gluing in a bar with tension.

Figure 7

Figure

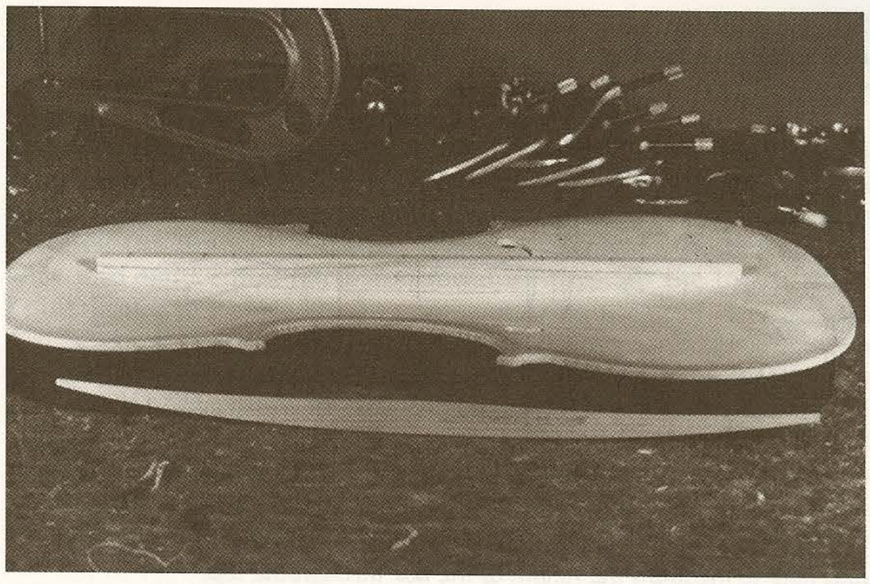

Figure 7. Bass bar template and the traced line on the bar.

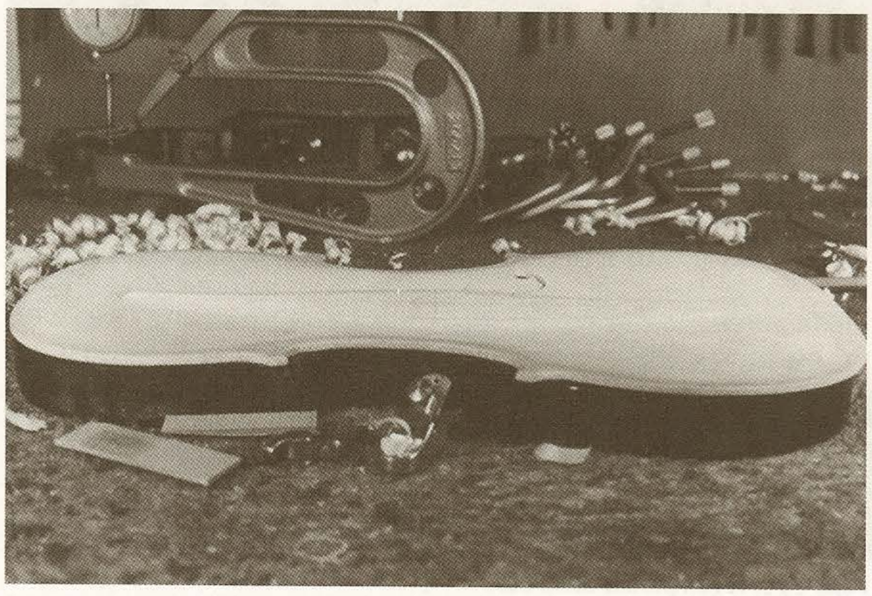

Figure 8. Shows the bar's trimmed down height and some tools used. Note the division of the bar into eight equal parts.

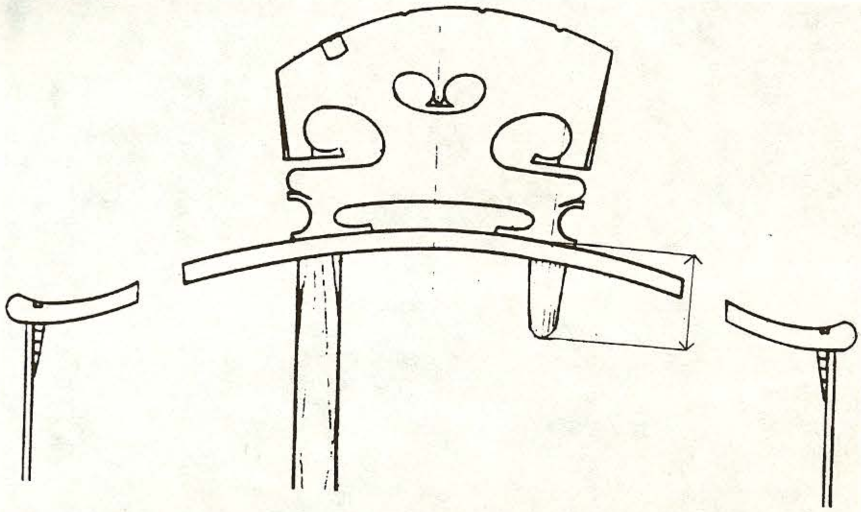

Figure 9. The relative position of the bridge, sound post, and bass bar, and how to measure the height of the bar through the top.

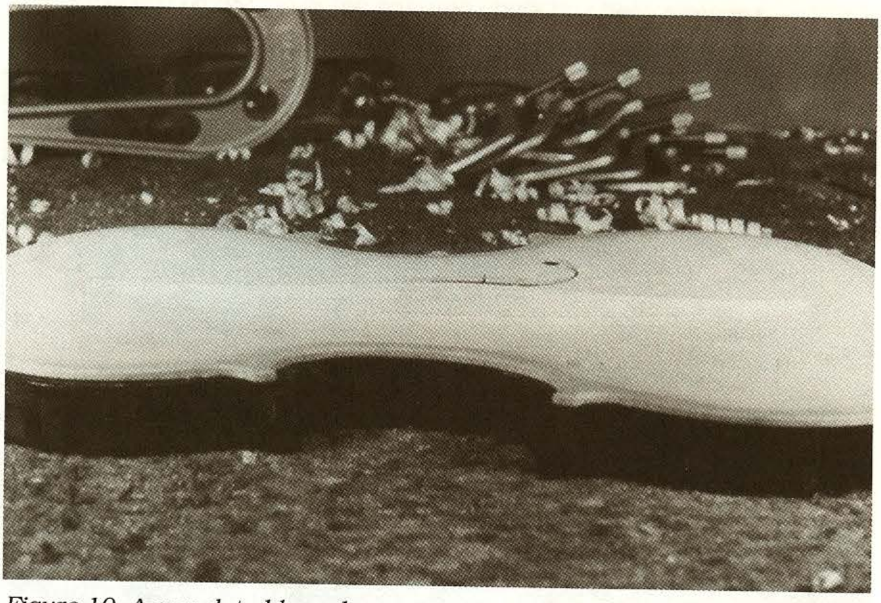

Figure 10. A completed bass bar.

curved cross section of the bar, which is the next thing. Once I am down to the shape I like and have sanded it smooth, I am looking at a slightly oversized bass bar, nearly finished in a very short time.

The slope across the arch can vary from instrument to instrument. This will give significantly different readings when measuring the height of the bass bar from the sides, so I measure through the top with a caliper (Figure 9). I divide the bar lengthwise into eight equal parts and measure through the top at these points (refer to Figure 8).

I know there has been much discussion about where to locate the highest point of the bar. Should it be at the bridge, the center, or somewhere in between? I really don't think there is a definite answer. A top that has a lot of flexibility in the upper and C bouts will be very happy with a full midsection and the high point at the center. Conversely, I think that a top that is strong in those areas will be happiest with a bar that has a broad sweep reaching its highest point at the bridge. The choice of wood for the top and bar, and the shape of the top, will enter into the evaluation as the shaping continues (Figure 10).

At this point, Bill will tell you about the experiment.

Dimensional and Acoustical Measurements and Observations

Bill Atwood: I am delighted to be here today to present the experiment that Tom and I came up with. To begin with, I'd like to go through a little bit of the motivation behind the experiment and what we thought we might see, as a precursor to what we actually found.

Our experiment has a narrow focus. We're not talking about all aspects of bass bars and how to tune them. We only considered tension and whether it is static or dynamic. These are physics terms. *Static* means playing a structural role, i. e., bass bar tension simply reduces the deformation in the top in the region of the bridge. *Dynamic* means changing the acoustical properties of the instrument.

Here I will confess that I had a prejudice going into this experiment for reasons that may come out in the question period. I thought the tension in the bass bar was mainly going to be a static property and would have little effect on the sound.

Our starting point was the question Tom posed: What's the effect of tension? We wanted to install several different bass bars in the same violin and control all the other parameters in the experiment to a degree such that we mainly measured the effects of tension. One part Tom left out was that we had to find a violin with which to do this. Tom was very reluctant to use a "junker"

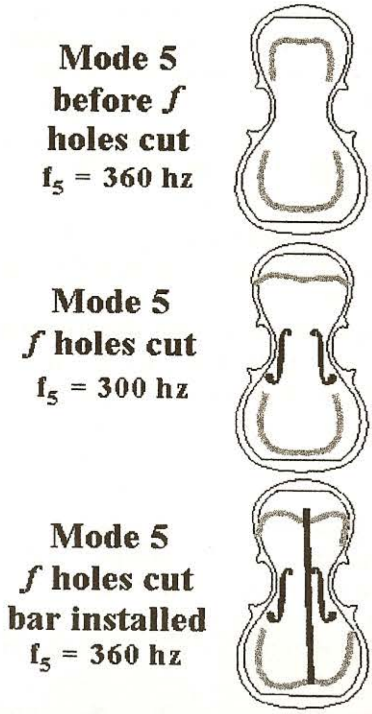

Figure 11. Mode 5 at various stages in working a top plate: before cutting f holes, after cutting f holes, and after bass bar installation.

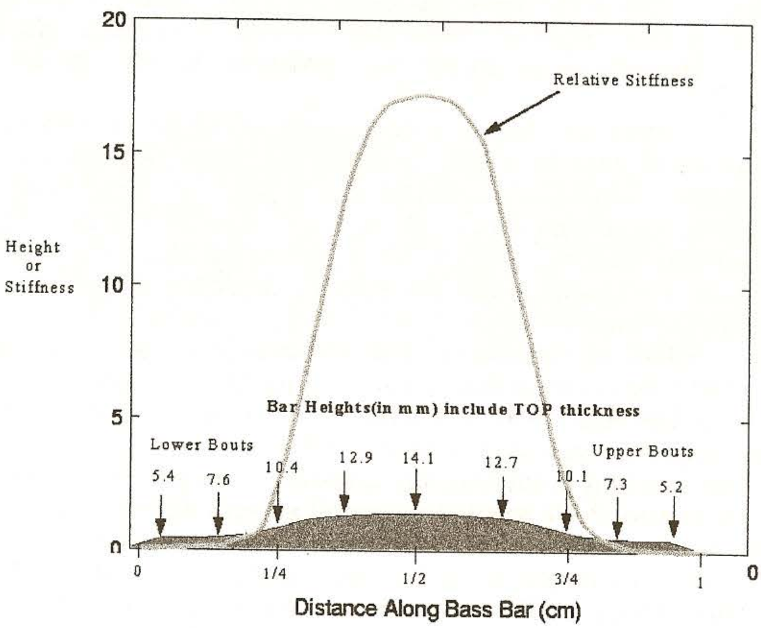

Figure 12. The height profile of the bass bar used in this experiment. The indicated heights include the thickness of the top. Also shown is the calculated stiffness profile for this bass bar.

for fear a poor quality violin would mask some effects. So he volunteered his wife's violin, which he had made for her in 1987.

For the static measurements, we decided to measure the arch height a few millimeters in front of the bridge for the free plate after the bar was installed, and for various loading conditions: sound post in, sound post not in, strung up, etc. For the dynamic measurements, we would measure free-plate eigenmodes, as well as measure the acoustic properties of the assembled violin both objectively as well as subjectively.

I am not advocating that you should become plate tuners, but those who do plate tuning will recognize the following sequence (Figure 11).[4] In some sense, you might look at the bass bar in the top of the instrument as a cure for cutting the *f* holes. Why do I say that? When you cut the *f* holes in the top, you destroy in large measure the longitudinal stiffness. You can see this by looking at the eigenmodes before you cut the *f* holes. You have a beautiful mode 5 shape and the plate is extremely resonant. Then you cut the *f* holes and mode 5 deforms, almost becoming a flat line in the upper bouts, and its frequency plummets by 50 to 60 Hz. After the bar is installed it comes back, not exactly to what it was prior to cutting the *f* holes but pretty close, and the eigenmode frequency is also pretty close to its former value as well.

One other interesting fact about bass bars is this simple rule: the stiffness increases as the cube of the thickness. I think many are somewhat insensitive to this or only sense it intuitively. When we talk about the stiffness of anything, whether it's a pencil or a yardstick, its stiffness increases as the cube of how thick it is—i. e., the (height) x (height) x (height). In a practical sense, this means if you make it twice as thick, it becomes eight times stiffer.

Now consider the profile of a bass bar overlaid with its relative stiffness end-to-end as shown in Figure 12. The numbers written on the profile are the numbers that were used in the experiment. These heights are measured through the top in the manner that Tom described and range from 5.2 to 5.4 mm at the ends to about 14 mm in the center. The ratio center-to-end cubed is over a factor of 20! Almost all of the stiffening action is occurring in the middle half of the plate, not at the ends. I'm not saying that small residue stiffening at the ends isn't important, but it's small compared to that in the center.

As Tom mentioned, this presentation is not about tuning bass bars. Tom used his standard technique for tuning the first bar (no tension). All subsequent bars, whether they had moderate tension or a lot of tension, were simply carved to the same height profile. As mentioned before, the bars were cut side by side from a billet of wood to reduce the variables. As it turns out, there is a

Figure 13. Free plate mode 2 on violin top set up on the shaker table.

Figure 14. Free plate mode 5 on violin top set up on the shaker table.

Case	Tension	Free Plate	Plate on Ribs	Sound Post Installed	Strung up to Tension
1	0.00 mm	16.1	16.18	16.41	16.17
2	1.25 mm	16.3	16.20	16.49	16.27
3	2.25 mm	16.4	16.38	16.64	16.45

Table 1. Summary of the dimensional measurements made on the violin top for the three cases of bass bar tension.

monitor of how similar the wood was and how well Tom reproduced the bar installation.

The first issue was to measure the mechanical or static properties. To this end, we constructed a simple U-shaped device that could be clamped to the edges of the violin in the C bouts with a hole in the middle of the cross bar to provide a platform through which we could drop the depth end of a caliper to the top of the instrument. This would allow us to measure the arch heights with the top attached to the instrument. To minimize the error, we did these measurements in the following order: fully strung up; tension off the strings; and finally with the sound post knocked over. In this way we didn't have to remove the measuring tool and hence minimized any systematic changes that might be introduced.

The three cases that we tried were: no tension (zero); 1.25 mm of tension (which we'll refer to as moderate); and 2.25 mm (a lot of tension). The free-plate arch measurements are shown in column 3 of Table 1. The variation is less than a millimeter. Column 4 shows the arch heights, after the top was glued onto the ribs with no sound post and not strung up. Again, there's a few tenths of a millimeter of variation. By and large, we saw very little deformation in the plates caused by tensions over this range.

It's interesting to note that Tom recalls when he first made this violin in 1987 that the arch height was 15.5 mm. Our measurements show that the top has been noticeably deformed since 1987. It is also interesting to compare the next two columns in Table 1, "sound post installed" and after being "strung up." These data show that when you put in the sound post the plate goes up, and when you put on the strings, the plate comes back down. As anticipated, we found that bass bar tension can partially compensate for the downward pressure of the strings on the bridge. We also noted that, for the highest tensioned bar, the upper left-hand wing of the *f* hole was slightly "proud" (raised), while for the zero-tensioned case it was slightly depressed relative to the table.

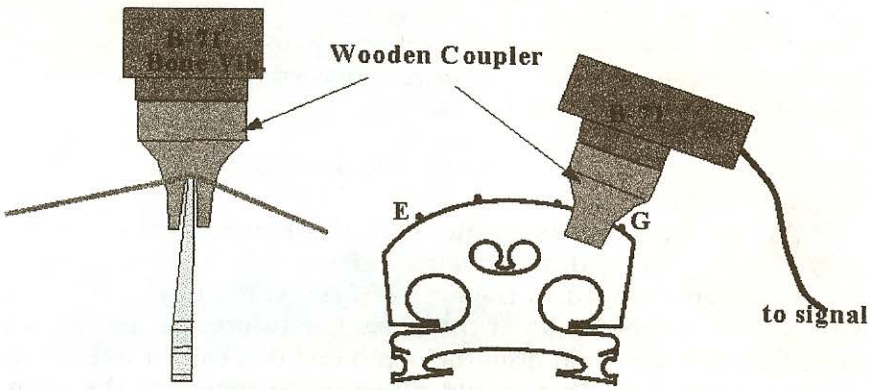

Figure 15. The acoustic transducer (Model B-71 bone vibrator) coupled to the violin bridge via a small wooden adapter.

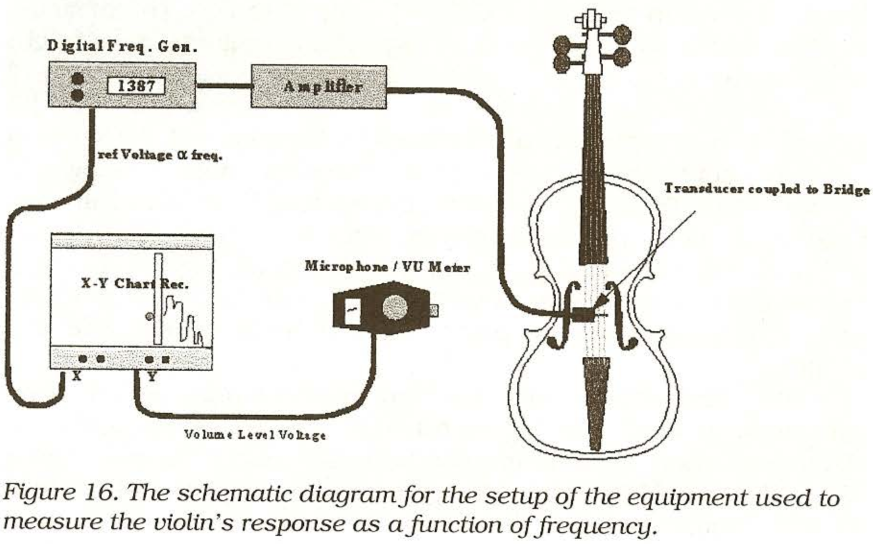

Figure 16. The schematic diagram for the setup of the equipment used to measure the violin's response as a function of frequency.

Case	Tension	Mode 1	Mode 2	Mode 5
1	0.0	80	150	350
2	1.25	80	149	354
3	2.25	79	151	352

Table 2. Summary of free plate eigenmode measurements for the three cases of bass bar tension.

I now turn to acoustical measurements. We recorded eigenmodes 1, 2, and 5 using the standard shaker table technique. Modes 2 and 5 for the top of the violin are shown in Figures 13 and 14. The shapes are typical for these modes. These photos also serve to show the setup of the shaker table in my shop. Covered up by the plate is the hole cut in the table and the speaker mounted underneath. Also, there are four bits of foam rubber on which you can place a plate over the speaker for testing.

Now we come to the issue of how reproducible was Tom's work. In Table 2 we have listed the eigenmode frequencies that were measured for the three cases examined. As you can see, there are no significant changes in the eigenmode. This was quite remarkable given the fact that for neither case with tension was there any a priori tuning. The bars were simply put in to be dimensionally the same as for case 1. What we see here is that bass bar tension seems to have little or no effect on the free-plate eigenmodes commonly used in violin making. What was even more surprising was that we observed negligible changes in the mode shapes as well. For the first case, we marked the shapes of mode 2 and mode 5 on the plate in pencil. When we measured cases 2 and 3—moderate tension and a lot of tension—it was easy to compare the nodal lines with existing pencil lines. They coincided.

We felt that after a violin is subjected to this kind of open top surgery, it needs a certain amount of settling time. We tried to speed this along by artificially vibrating the violin after it had been reassembled, using a hearing aid device called a bone vibrator.[5] We drove the vibrator with a square wave at a frequency of approximately 220 Hz and the vibrator was coupled to the bridge as shown in Figure 15. In all three cases the violin was vibrated with a power level applied to the vibrator of about one watt for 24 hours.

The acoustic measurements made on the assembled violin were divided into two areas: subjective and objective. A problem that frequently occurs in the violin world when evaluating tone is that one person's "harsh and brittle" is another person's "bright and projecting." Our attempt to be quantitative will, we hope,

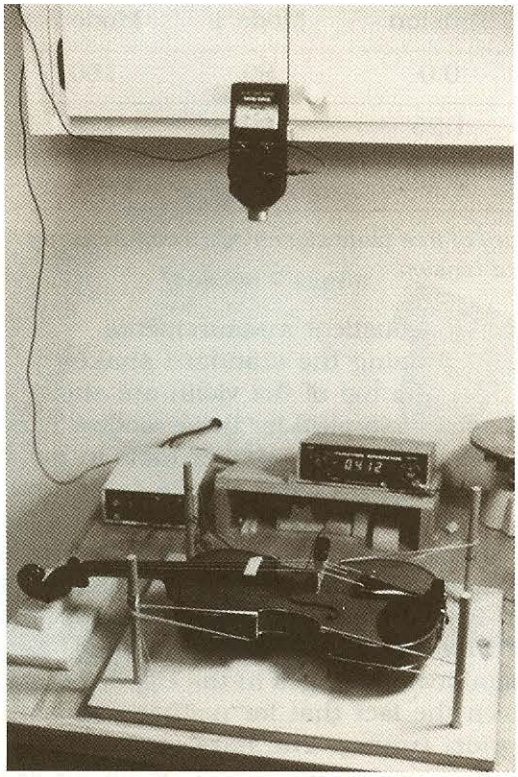

Figure 17. The objective evaluation setup with the signal generator, bone vibrator attached to the violin bridge, and sound-level meter attached to an X-Y chart recorder (in other room).

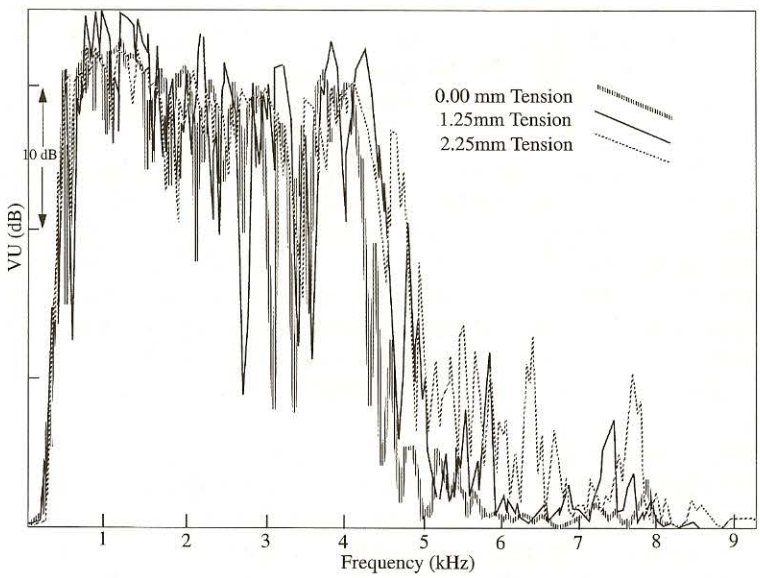

Figure 18. Response curves versus frequency are shown for three cases of bass bars. Note that there is progressively more response with increasing tension in the region above 5 kHz.

sharpen the subjective evaluations now given.

I played a two-and-a-half-octave chromatic scale and a simple piece for each case. We recorded these so that we could review them later. Tom and I found that our subjective tonal evaluations were in all cases very similar—different words, but the same content. For the zero-tension case, the sound was quite flat and didn't have a lot of color. For the moderate case, it seemed that the sound was closer to what we were used to in a good violin sound. And finally, for the overly tensioned bar, the sound seemed a little overly bright, perhaps even a little brittle as you might expect in a brand new violin. It was obvious to both of us that the different tensioned bars were affecting the violin's tone.

For the objective evaluations we used a signal generator. We drove the violin with the bone vibrator using a pure tone (sine wave) at the bridge to minimize the issue of harmonics. The violin output was monitored with a sound-level meter, and both the sound-level meter and the signal generator were connected to an X-Y chart recorder. This setup is shown in Figure 16. We developed an automated procedure that scanned the input frequency and measured the relative sound level that the violin was making as a function of frequency. Figure 17 shows this setup. The strings were damped with a small piece of foam rubber, and the sound-level meter was placed about 50 cm above the violin. The chart recorder was located in the next room since we noticed that the chart recorder "liked to talk to the microphone," causing a certain amount of "chart-recorded jitter." The violin was suspended from four posts with rubber bands.

It is important to note here that we do not claim that this setup makes absolute response measurements of violins. This is a very difficult business and one needs to go to great extremes to calibrate the equipment, the transfer functions, and locate the violin and microphone inside a sound-absorbing environment so that you are not listening to echoes off the wall, etc. (namely, you have to do it in an anichoidal chamber). What we were looking for were changes and, provided that we have the same setup every time, then I claim that this apparatus is appropriate for observing changes.

Figure 18 shows the frequency response for the three cases of bass bar tension. We scanned from 100 Hz to almost 10 kHz. The vertical scale is in units of decibels and each one of these major divisions is approximately 10 decibels. Up to 5 kHz, you can see the typical forest of resonances. Then, for this setup, it tends to fall off. I suspect that this is the frequency response of the hearing aid device rather than the violin.

The plot for the zero-tension bar shows the lowest response in the upper frequency range (> 5kHz). What caught our attention was that the upper frequency range has more response and more

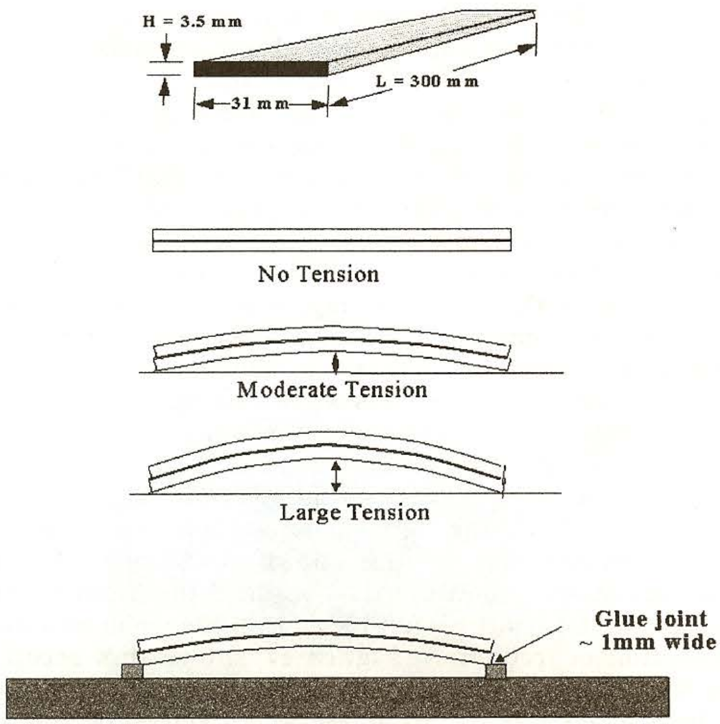

Figure 19. A sketch of the simple beams and how they were assembled with varying degrees of tension.

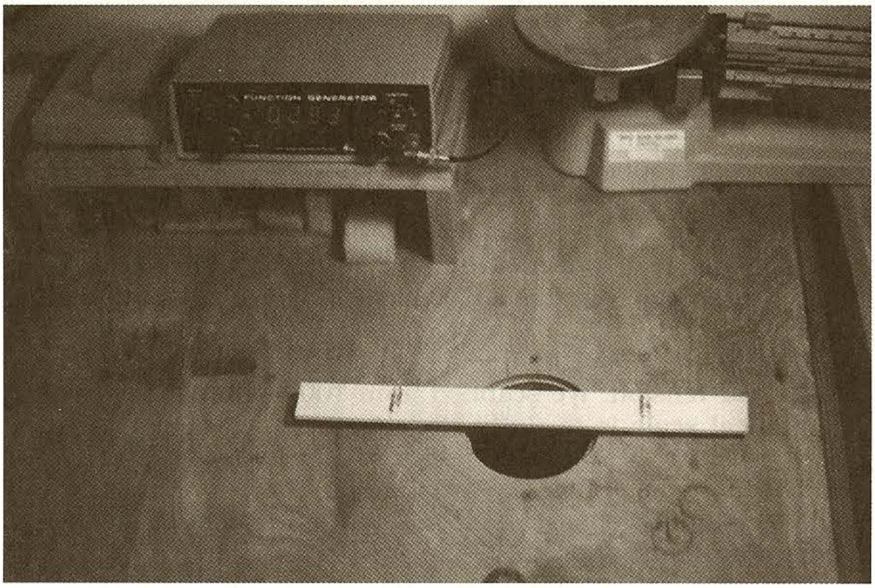

Figure 20. Measurement of a sample beam on the shaker table.

peaks with increased tension. So, in the assembled violin, tension does have an effect and it is quite pronounced. Some of the peaks above 5 kHz changed by 10 decibels for the higher tensioned bar. That's a lot.

So what's going on? I thought there would be no dynamic effects and we measured no dynamic effects for free plates. But when the strung up violin was measured, there were large dynamic effects, particularly at high frequency, and it seemed that there probably was some optimum to be found.

To help us understand what we were seeing, we tried to come up with an even simpler experiment, one that would be amenable to calculation. To this end, we prepared some samples of quartered spruce 30 cm long, 3 cm wide, and 3.5 mm high with the grain running lengthwise (Figure 19). These samples were trimmed until all had about the same lowest frequency. The lowest eigenmode for a simple beam has two modal lines running across the large face. If you hold it at around the one-quarter point and tap it in the middle, you will hear a distinct note corresponding to the lowest eigenmode. Instead of tapping, we used my shaker table to measure resonance frequencies. Figure 20 shows one of the samples set up over the table. You can see two nodal lines and you can read the frequency of the generator. For this case, there is a mathematical formula that relates the measured frequency with the speed of sound, how thick it is, and how long it is:

$$f_0 = 1.067\ c_s h/l^2$$

(frequency = 1.067 (speed of sound) x (height)/(length x length))

All the samples were adjusted so that their lowest frequency eigenmode fell in a narrow range around 220 Hz. Pairs were glued together for three different cases: zero tension, "moderate tension" of 2.6 mm, and finally an extreme case of almost 4 mm (see Figure 19). After forming these pairs, the resultant beams were remeasured. Next we tried to simulate what was happening when the top is glued onto the violin. We glued the edges of the beams onto a solid support and again measured the lowest eigenmode frequencies. It turns out that this was also amenable to calculation and there is a formula that is very similar to the one above, except the constant, 1.067, is about half of what it is for the free samples. In Table 3 we summarize the data gathered for this simple beam experiment.

Recalling that the pitch rises proportional to the height, it is easy to guess that the frequencies for the pair beams will simply be the sum of the pitches for the individual free samples. How well we did can be estimated by how good this match is. (Case 2 is a little bit off, but for the other two it was "spot on.") This is

Case	Tension	$f_0(1/2\text{'s})$	$f_0(\text{free})$	$f_0(\text{glued})$
1	0.0 mm	218	436	215
		218		(192)
2	2.6 mm	219	446	231
		221		
3	3.8 mm	222	444	247
		222		

Table 3. Summary of measurements made on paired beam samples.

similar to what we observed for the violin's top: for the cases where we bent the pieces of wood (i. e., added tension), there is effectively no change in the free-bar eigenmode frequencies. The last column shows the frequencies we observed when the ends of the beams were glued down. If the glued down ends were constrained hinge-like, then we would have expected 192 Hz for the first case, rather than the measured 215 Hz. We suspect that the difference between these two numbers is that the glue joints are not perfect hinges. The glue joint, in fact, stiffens the coupling of the beam to the supports. To the extent that we clamp the two ends of the beam, the frequency will migrate all the way back up to the free-bar frequency.

For the two trials with tension, the last column in Table 3 shows a similar pattern to what was observed with the violin: as the bending (tension) is increased, the natural response frequencies rise. These frequency changes are quite significant.

To summarize, we have made a systematic study to understand the effects of tension in bass bars. The data we have indicate that:

1) There are small but observable static effects (at the quarter of a millimeter level) in deforming the plates;

2) The tension in the bass bar has little effect on free-plate tuning; but

3) In assembled violins, both our subjective as well as our objective data indicate that increased tension results in increased high-frequency response.

I have heard it said (maybe the restorers in the audience can elaborate on this) that sometimes the old Italian instruments can be partially restored by replacing the bass bar.

I'll end by saying that both Tom and I found that the combination of the traditional maker expertise and the scientific approach was extremely rewarding.

Discussion

John Masters: When you took your twin strips and glued them together under varying amounts of tension, did you check to see if the nodes were at the approximate quarter point, or if they seemed to change much in the free-stressed bars before you glued the ends down? In other words, I'm wondering if the relative position of the ends of the bar at the nodes changed and if that would have anything to do with the rising of the resonance when you glued the ends of these paired bars down.

Mr. Atwood: In the case of the bent bars, it was not possible to observe the nodal lines because it was on a curved surface and the standard technique of the glitter would just roll off. So, in fact, we did not measure those nodal lines.

Mr. Masters: I understand. Would you guess that there would be a correspondence between the relative change in those nodes and where they were glued down at the ends? You don't think so?

Mr. Atwood: Given that the frequencies came out as you would have expected from the composition of the bars that were put together, I have no reason to suspect that the nodal lines wouldn't come out essentially at the correct 23.7% points (from the ends) on the bar as well.

Mr. Masters: What do you attribute this rise in resonance to?

Mr. Atwood: I'm not confident at this point that I have the correct explanation of the effect and so won't comment.

Mr. Masters: Do you think you biased the system to a nonlinear situation where you might have raised the frequencies . . .

Mr. Atwood: No, I don't think so.

Mr. Masters: So you don't have experimental results to support either conclusion. But you won't offer an explanation that you think might explain it.

Mr. Atwood: No. The data we took, I think, stand on their own merits.

Mr. Masters: You don't want to attribute it to any particular thing?

Mr. Atwood: I'm not willing to make guesses in this forum that may later turn out to be wrong.

Mr. Masters: Thank you.

David Chrapkiewicz: All this assumes that free-plate eigenmodes have meaning and tuning has meaning. If you back up a bit and the effect was to measure tension, assuming that the pieces of the bass bar were all identical, cut from the same piece of wood. Instead of tuning the bass bar in the violin if it were dimensionally put in exactly the same, was any effort made to measure any increase in stiffness, maybe a localized stiffness which would represent an increase in tension due to springing? You can compensate for an increase in tension by tuning the bass bar. So you may defeat one by doing another.

Mr. Atwood: Yes, if Tom had individually tuned these bars with his, we could have come out with a very different result. We did not measure the spring constant of the bar, to answer your question directly. Maybe we should have.

Mr. Chrapkiewicz: What I'm also talking about is each bass bar being identical in terms of stiffness, mass, and length (dimensionally) and throwing away the tuning. Do you understand what I'm getting at?

Mr. Atwood: Yes, but that's effectively what we did or, at least, what we tried to do. And the experimental evidence that grades us on how well we did that, I claim, are those free-plate eigenmodes that came out as they did.

Mr. Croen: The question I was curious about was would a bar with tension be able to have less mass than a bar without tension in order to have the same harmonic signature. Part of the difficulty was that we had to keep taking the top off and putting it back on. Before removing the extreme tension bar I tuned it the same as the first bar (no tension) and was able to reduce it by about .5 mm in order to achieve the same harmonic signature. We did not then put the top back on, but with the last bar (1.25 tension) that is actually what I am going to do. I am going to retune it and then put the violin back together and we'll see if there is a difference between zero and 1.25 that way. I suspect that there will be. Seems logical, but we haven't actually demonstrated that yet.

Joseph Curtin: Beautifully done experiment, I really enjoyed that. I thought you did great work. I'm curious, as an addendum to it, whether some of the changes in a free plate caused by tension could be illustrated by measuring the higher modes of the free plate rather than just 2 and 5?

Mr. Atwood: Excellent. You should have been part of the experimental team. What you are saying occurred to us, exactly. We were short-sighted in only measuring the first three eigenmodes. We passed up a golden opportunity, I should say, because Tom's wife is not going to let us do it again.

Haio Meyer: I agree with Joe's compliment. I think this is very important work. Coming back to the speaker before Joe who was a bit skeptical about the use of tuning, if he was skeptical, he had some right to be. But I think your work now makes it more useful than it was before because we all have tuned plates exactly the same and found that the violin, even if you use the same wood, came out differently. I found that even if I tuned the same, they often came out differently, especially in the high-frequency region. That's because until now I was rather sloppy in defining my end spring. I will be less sloppy in the future. Thank you.

Mr. Atwood: I would like to make another comment on that. I gave a paper at the Catgut Michigan meeting in which I tried to emphasize exactly this point. Free plate tuning is really a starting point. It does not, in fact, determine the acoustics of the finished violin without substantive intermediary steps.

Evan Smythe: As far as removing plates, for those crazy experimenters like myself, if you will mix up egg whites in the manner that Sam Compton gives for your sealer with liquid hide glue, if you mix it in the right proportion, when you are ready to remove the top, just a slight squeeze and the top will snap right back off with no damage. It works excellently, even if you take it off a hundred times.

Mr. Atwood: I should let Tom talk to this but that would have been an excellent way to pop tops on and off for purposes of experiments like this, but I think you probably want it on a little more solidly if it was going out the door in a customer's hand.

Mr. Smythe: Absolutely. For a control, it seems that the high frequency when the bar is glued down, from my experience, would be that a curved piece of wood glued down at the ends could practically be stood upon while a flat piece will cave in. A flat one will have a positive, negative vibrational tendency, whereas just the fact that it is arched will raise the frequency as soon as you glue it down. For a control, to have bent the pieces of wood, glued them down, and measured the frequency and then sprung a piece against that with the same curve when you're done—I'm not sure how conclusive the results are in that manner, but I can *definitely see a rise in frequency just in the fact that the wood* was bent. Whether the fact that it was sprung or not made any difference, I wouldn't know.

Mr. Atwood: You are getting into the area that I suspect has to do with what is happening: that the rise in frequency was in fact connected with the shape coupled with the boundary conditions on the bars. Roman arches are much stronger than planks.

Mr. Smythe: Right. So I would assume by springing the bar in there is a slight deformation in the area around the bar and that slight deformation in the plate causes the strength which . . .

Mr. Atwood: The trouble with that theory is that you saw the size of the deformations compared to the overall arch height: a few tenths of a millimeter to a quarter of a millimeter. But in fact that may be the answer. It may be that those slight changes in the arching shape induced by the tension in the bar are the root cause of what we're seeing here. Without studying it more carefully, I'm unwilling to commit to that.

Mr. Smythe: I have a friend who is a piano maker who insists that the bar in a piano—almost the size of your arm—has to be sprung or the piano will have no brilliance. He's positive that that has to be done on the piano.

Jerry Passowitz: You mentioned that you played the instrument artificially between bars. Did you have your measurements before or after the instruments were played in?

Mr. Atwood: Both.

Mr. Passowitz: Did the measurements change?

Mr. Atwood: They changed a lot, but this is not a lecture on acoustical aging.

Eric Meyer: I was wondering how independent of each other were your subjective appraisals?

Mr. Atwood: Not very. The violinist was me.

Mr. Meyer: Did you compare notes while the appraisal was going on?

Mr. Atwood: We sat around and talked about it.

Mr. Croen: We were open and honest enough with each other that we could say just what was on our minds. We had similar opinions. Not always exactly the same but they were similar; enough so that the trend was very clear.

Mr. Meyer: It would help, though, if you did your opinions separately. If you wrote them down and then got back together and compared them.

Mr. Croen: We did that for the first one but our comments were nearly the same, so the next time we felt a little more at ease about commenting as we were writing.

Mr. Atwood: We have the tape, Eric.

Mr. Meyer: I want to hear that tape.

Mr. Atwood: You may not after you listen to my playing.

Mr. Meyer: Good work you guys.

Mr. Masters: When you speak of tension, you speak of deforming the ends of the bar toward the top and as you mentioned, at the beginning, that that might vary by how thick you left the bar when you made the compression. It seems to me that you are introducing a shear between the two components, there in the glue joint. Did you do anything to make any consideration or measurements on the relative effects of just this end-wise compression which could be very small if you trimmed the bar before you compressed it? That versus the shear that you introduced, make the shear dominate over the compression at the ends of the bar when you compress it in.

Mr. Croen: I'm not sure if I can answer the question. The process that I used in gluing all the bars was the same. I didn't change the dimension of the bars.

Mr. Masters: Mostly the top bent rather than the bar when you compressed the clamps, isn't that right?

Mr. Croen: Probably. But again, in all three cases, the bar was the same size.

Mr. Masters: Yes, and you still have the changes and wanted to measure only changes. The word tension has been used for a long time without specifying what it is and I'm just asking if it's possible that the effect of tension is more due to this introduced shear rather than the simple compression at the ends of the bar?

Mr. Atwood: First of all, you are correct in identifying the shear in the glue joint as the source of any of the arch deformations we have seen in the finished product. There is no other force in the problem that's around to deform the top. You are also correct in the example that Tom alluded to in the case of the French technique where they were carving the bar down and then mutually bending the two to each other.

Mr. Masters: They would have less shear?

Mr. Atwood: They would have less shear in that joint and, as a corollary, less deformation of the outside of the violin as well. We didn't do that experiment so it is hard to make a comment on it. As I said in the beginning, we tried to make a very sharply focused experiment. The tension that Tom used is the traditional one and it is the one that people usually discuss, and so we decided to answer the Weisshaar question: How much tension? Now at least we know the sine of what it's doing.

Mr. Masters: Can I make a brief comment on how I've experimented to introduce the shear without worrying about how much tension there is at the end? That is to compress the top end to end and collapse it somewhat and fit a bar exactly without reference to how tall the bar is going to, just like the perfect fit on a compressed top. There you are introducing your shear without needing to know how much compression is being . . . or how thin the bar is when you glue it in. It's an interesting thing to try.

Mr. Croen: Thanks, John. We have to stop now. Thank you all for your attention and comments.

1. Antonio Bagatella, *Rules for the Construction of Violins, Violas, Cellos, and Double Basses* (Padova, 1782).

2. Count Ignazio Cozio di Salabue, *Technical Studies in the Arts of Musical Instrument Making*, Andrew Dipper and David Woodrow (trans.), 1987.

3. Hans Weisshaar and Margaret Shipman, *Violin Restoration: A Manual for Violin Makers*, 1988.

4. *Research Papers in Violin Acoustics, 1975–1993*, edited by Carleen Hutchins and Virginia Benade (Acoustical Society of America, 1997).

5. Model B-71, Sensory Devices, Inc., Radioear Corp., Main Street, New Eagle, PA 15067.