Testing of Acoustic Stringed Musical Instruments: Part 4

by G. Bissinger

MODERN VIBRATION MEASUREMENT TECHNIQUES FOR BOWED STRING INSTRUMENTS

Almost two centuries of continuous scientific investigation make the violin the most studied string instrument by far, and probably the most studied of all musical instruments. The vibrational complexity of the violin, where interior air modes vie with corpus and vibro-acoustically coupled modes to produce the actual sound, is entangled with the transformation of vibrational energy into acoustic energy to produce sound. To date no quantitative technique has been successful in reliably describing or predicting the overall quality of the violin. Consequently as experimental techniques have evolved, scientific research has also. The current technology can now offer automation, low-damping support fixtures to separate out radiation damping, zero-mass-loading excitation and response, and simultaneous modal and acoustical analysis on the violin.

PRIOR RESEARCH

The violin has been a relatively mature musical instrument for 3 centuries, with only minor modifications over that time; the “bible” for construction of the violin has been available for over a century.[1] For a comprehensive historical review the reader is referred to the 1983 article on almost two centuries of violin research by Hutchins,[2] published just prior to the first experimental modal analysis (EMA). Names familiar to those in physics or engineering fields were quite prominent in this history, yet the empirical knowledge base of makers is still the dominant contributor to the quality of the assembled instrument.

Some historical methods for testing violins are still of interest today because they can be related to the normal mode properties of various substructures. Although surprisingly little detail is known about the actual evolution of the instrument we today call the violin, we do know that violin makers commonly employed top and back plate “tap tones” in their construction practices early on. For example Felix Savart noted in 1840 that tap tone results for some old Italian violin top and back plates had a certain pattern: “. . . we have found that the sound varies in good violins between C sharp 3 and D3 for the belly [top] and for the back between D3 and D sharp 3, so that there is always a difference between them of a half or whole tone.”[3] The lore is that plates were held in a certain way and tapped in a certain place and the pitch, duration, and loudness of the tap tone was judged by ear. These are certainly suggestive of frequency-, damping- and mode-shape- related properties to anyone working in vibration analysis. Little information is available on how legendary makers tuned their plates, or what they tuned to, except through retrospective analyses of free plates from dissembled instruments. This can be problematical because the wood has aged and changed, many top plates in old violins have been modified by installation of a different bass bar (a small interior stiffening member running about 2/3rds of the top plate length, offset to lie under the bridge foot of the lowest pitch string), and the vibrational history considerations because playing a violin changes its vibratory behavior. Over these past centuries new technologies and techniques, applied as they were developed, helped us to understand the vibration of substructures, as well as the vibrations and acoustic radiation from the assembled violin. Let us briefly examine some of these and then conclude with the thoroughly modern testing and analysis techniques we are now capable of.

CHLADNI OR NODAL LINE PATTERNS

Scientific measurements of violin vibrational properties really did not start until the early 1800s when Felix Savart started observing Chladni patterns on horizontally mounted, powder-covered violin top and back plates bowed at various places to excite different eigenmodes. This technique works well for the top and back plates which have concave surfaces. Unfortunately the assembled instrument presents mostly convex surfaces and powder rolls or slides off when the instrument is vibrated, somewhat diminishing the utility of this method.

The Chladni pattern technique underwent a modern rejuvenation in the latter part of the 20th century when loudspeakers capable of inducing sufficient plate motion (with sufficiently powerful electronics) became readily available and affordable. This meant that the plates did not have to be clamped for mechanical excitation, but could float over the speaker on small foam supports and be acoustically driven, giving a much better approximation to “free-free.” The advent of lasers combined with the techniques of holography heightened the interest in the free plate eigenmodes. These more cumbersome holographic interferometry techniques gave results in excellent agreement with plate Chladni patterns and also provided information on mode vibrations of the assembled instrument.[4] Unfortunately the modes seen in the early holographic work suffered from serious boundary condition problems due to the necessity to clamp the plate or instrument firmly over an extended period.

The later development of “electronic” (speckle interferometry) holography techniques, some with reflective tape to enhance surface reflectivity, enabled real-time observation of the interference patterns.[5] This made holographic procedures far more useful, although at present these procedures typically only provide operating deflection shapes, not normal modes. Calibrated results appear possible with direct electro-mechanical excitation, but this introduces mass loading. Typically holographic measurements require a support system considerably stiffer than the favored low mass elastic

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This fourth part of the musical instrument series will be the final installment. The series was organized by Mark French of Robert Bosch Corporation and supported by a number of contributing authors.

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supports, introducing mode-dependent frequency and damping errors.

By 1981 the frequency and mode shapes obtained with Chladni pattern techniques were sufficiently well understood and popularized by Hutchins to warrant a Scientific American cover story.[6] Today many makers around the world incorporate these techniques into their plate tuning procedures. In fact Schleske, a German violinmaker, has taken this procedure one significant step further and pioneered a technique called "tonal copying."[7] With a violin of very desirable acoustic properties placed over an acoustic driver to excite the normal modes of the assembled violin, the frequencies *and* nodal line patterns of the prominent modes were noted. By duplicating this procedure on another violin, assembled but with the plates unvarnished, and then—from the *outside*—modifying the plate thickness in predetermined ways it is possible to place the desired mode shape at the desired frequency.

FE ANALYSES

While Chladni patterns were giving researchers some idea (frequency, mode shape, even qualitative estimates of damping) about which modes were being sought by makers employing tap tones, the concurrent development of finite element modeling capabilities made it possible to simulate plate vibrations as well as those of the assembled violin with[8] and without strings.[9] Rodgers made an extensive analysis of "areas of influence" on the top plate (typically spruce) and the back plate (typically maple) where material could be removed to raise or lower the desired mode frequencies.[10] These numerical simulations gave makers for the first time some guidelines to how much plate material to take off, and where, to achieve Chladni patterns (or tap tones) at certain frequencies (or pitches), and even achieve certain frequency relationships. Simulated modifications of an assembled violin (without strings) have also been performed by Roberts.[9] A hint of the synergism that can result from combining a good FE model with measurements of actual instruments (guitars) is seen in the works of Richardson and coworkers.[11] Future violin research will benefit greatly from the complementary strengths of FE simulations using a good solid model employing accurate material properties interactively combined with EMA.

"IDEAL" MEASUREMENT?

After all these years of research what can we say about the "ideal" way to measure the violin? Shouldn't the ideal vibration measurements be made under actual qualitative evaluation conditions, i.e., held and bowed, with chin rest and shoulder rest in place? Unfortunately even the most modern techniques are inundated by a torrent of serious experimental problems, e.g.:

- How similar are the violin's boundary conditions from violinist to violinist? Should there be a standard way to hold the violin? Is there a "standard" violinist?
- What is the effect of the chin rest or shoulder rest—both held in place by friction—on the response? Should there be a standard chin or shoulder rest? (To go with the standard violinist, of course.)
- What is the effect of the bow's pressure, hair contact width/orientation/position along the string, and vibrational response on the violin's mechanical response? Should the bow be put in contact with a string at all? If so, which one?
- Can reliable mode damping values for the violin be extracted when it is being held? Internal and especially radiation damping contributions could very well be overwhelmed by the "support" damping. Won't this muddle our ability to work back to material properties?
- How exactly does one do a modal analysis on a violin that is being held (and bowed?). Personal experience doing modal analysis on a held bow using fixed accelerometer/roving hammer setup clearly indicated that achieving reproducible hammer strikes on the sharply curved surface of a small, slightly wavering object can be a formidable task.[12] This—combined with the multi-hour time required for a complete modal analysis of a held violin—would tax the physical abilities, and patience, of both the measurer and the violinist.

Furthermore the inability to reliably "back out" the effect of all these effectively unspecifiable experimental boundary conditions from any finite element model offers a fundamental reason why violins are best measured in a "free-free" condition with an absolute minimum of fixture-support contact, and the constraints of chin and should rests, holding, bowing, etc. modeled independently, and later. The pioneering experimental modal analysis by Marshall in 1985 was the very first experiment to examine the violin's corpus normal modes in a satisfactory way, including the corpus' vibroacoustic response to interior cavity modes above the A0 (lowest air mode, a "breathing" mode, and the strongest cavity acoustic radiator).[13]

MAJOR EXPERIMENTAL CONSIDERATIONS

1. Where Does the Energy Go?

Good violins are the result of remarkable empirical compromises—light enough to respond strongly to the bowed string motions, strong enough not to collapse under string tension and vigorous bowing forces, *and* capable of producing a strong, pleasurable sound.

One of the defining characteristics of the materials chosen by makers for the top or back plate wood is the clear "ring" heard with an impulsive strike. This points unmistakably to makers worrying about the damping properties of the wood; logically we should do the same. Vibration measurements on the violin or its substructures must provide reliable damping values to be really valuable to the maker. Unfortunately most measurements fail to do this because practical considerations—cost, negligence, or haste—intrude.

Reliable damping may well be the least important mode property for most people, and it certainly is one of the hardest to obtain unless stringent measures are taken in designing the support fixture and in the data acquisition and analysis. However, buried inside the measured damping is one of the key properties of each violin's normal modes, its radiation efficiency, i.e., the fraction of the mode's vibrational energy converted into acoustic energy. Although they may agree on little else about a violin's sound, professional soloists want a loud, projective instrument.

A violin supported in a "free-free" manner has three main energy loss routes, viz., to the support fixture, to internal energy (heat) or to acoustic radiation, each of which contributes proportionately to the total damping, i.e., $\zeta_{\text{tot}} = \zeta_{\text{fix}} + \zeta_{\text{int}} + \zeta_{\text{rad}}$. ζ_{tot} is of course what we measure. If it is possible to reduce fixture losses to a negligible level (~5%) then radiation efficiency can be obtained from $R_{\text{eff}} = \zeta_{\text{rad}}/\zeta_{\text{tot}} - \zeta_{\text{int}}/\zeta_{\text{tot}}$. Assuming we have done everything right experimentally (see Figure 1), if a close-by mode does not radiate well its measured damping must be very close to its internal damping, i.e., $\zeta_{\text{tot}}\ \zeta_{\text{int}}$. Hence it is possible by indirect means to extract from the measured damping a direct measure of radiation efficiency, mode-by-mode. The virtues of a properly designed support fixture for the violin (or any other device) could not be clearer.[14] Of course R_{eff} can also be measured directly using calibrated microphones covering a sphere around the violin.

2. Load Limits

Why is zero-mass loading important if we can back out the effect of mass attachments in our model? Two good reasons:

- *Technical limits*—there are always limits on what we can measure due to inaccessibility, time limitations, cost, etc. A mass attachment really requires multi-directional measurements to eliminate not only the mass but also its **moments**, extending the time and difficulty of the measurements. And the connection must be accurately specified.
- *Physical limits*—sometimes choices are limited by physical processes. For example the violin bridge is the main entry point for the string energy, and modes that cannot be driven from the bridge are hardly of primary importance. This makes the bridge an obvious driving point. Yet the bridge is exquisitely sensitive to mass loading.

So a stinger driver is not really feasible because we could not feel confident of backing out its mass loading effect. Similarly a response device should not be attached to the bridge. Since acoustic excitation does not give calibrated results, we are left with the force hammer as the excitation method, and of the zero-mass loading response transducers capable of calibrated measurements, the (scanning) laser Doppler vibrometer (SLDV) is the transducer of choice.

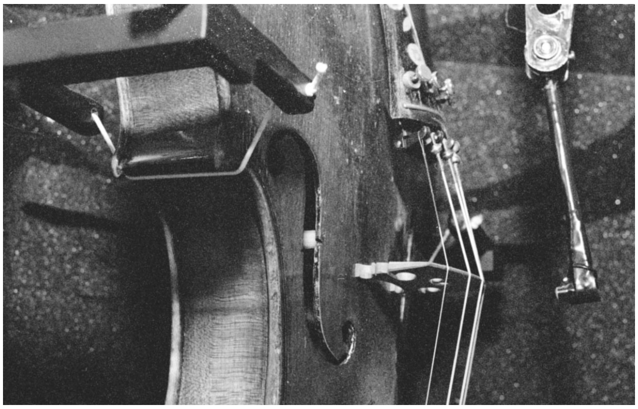

Fig. 1: Support fixture with low mass, low damping, flexible support elastics placed close to hammer strike axis to minimize torque, and subsequent rigid body rotations

3. To Rove or not to Rove?

Which is better: roving hammer—fixed laser vibrometer, or roving LDV (SLDV)—fixed hammer? It is easier, faster, and more reliable to fix the hammer position and scan with the laser beam. Hand strikes with a mini-force hammer on a violin are inherently unreliable—position, direction and force levels vary widely.[15] Automatic striking mechanisms for the force hammer still require positioning, and even then potentially impossible situations such as excitation by a force hammer at an oblique angle to the surface, or under the strings, must be faced. With readily available autohammers that can dependably positioned, and scanning laser systems, the burden of repeatability is shifted to the roving response transducer, the SLDV. Here the major hindrance is the cost of the laser system hardware and software, and the ever-present speckle dropout problem, which does have some palliative software remedies.

A FINAL CAUTION

The mechanical ➧ acoustic ➧ sound "chain" reminds us that violin quality evaluations are based primarily on the *sound* while our measurements are only of normal mode vibrations. It appears impossible to work the chain **backwards** because of the multiple intervening steps between vibration initiation and perceived sound. Even if the chain were simplified to two primary elements[16]—how effectively the energy gets from the vibrating string (which makes no sound) to the body of the violin (e.g., the bridge-corpus frequency response function), and then how effectively it gets from the body into the air (e.g., radiation efficiency)—these are "independent," so the acoustic output varies as the product of the two, making individual contributions un-separable. However, simple acoustic measurements such as single microphone, room-averaged acoustic pressures measured for hammer-impact excitation at the bridge can give substantial information on the radiative properties of individual normal modes, as can normal mode boundary element method acoustic calculations.[16]

THOROUGHLY MODERN MODAL

If we gather up the parts outlined above, a modern modal analysis system like that shown in Figure 2 is one possible result. This system is the result of an extended development effort: i) an automated excitation-response data acquisition system, ii) a low-damping, torque-minimization support fixture that also mounts the autohammer system, iii) an anechoic chamber, iv) a violin positioning system to allow the SLDV to scan all violin surfaces, v) multi-microphone acoustic measurements over a sphere by a rotating microphone array, vi) simultaneous vibration and acoustic measurements to extract radiation efficiency and directivity. Of course, violins are not the only string instruments that could be measured this way; guitars are perfectly suitable too. Unfortunately the technical limitations of our apparatus require larger instruments to be measured outside the anechoic chamber in a separate support fixture.

CONCLUSIONS

Modern modal analysis techniques along with companion finite element simulations offer a normal mode (and hence ultimately materials-based) approach to our understanding

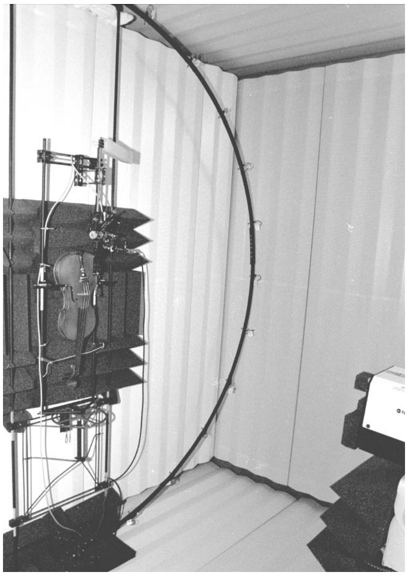

Fig. 2: Automated normal mode vibration and acoustical measurements system for violin, inside anechoic chamber

of the violin vibrations and accompanying acoustic output that is new in the long history of violin research. With the experimental techniques presently available it is possible to at least envision how to elicit the four material elements essential to creating an accurate, violin-specific solid model: substructure-specific *density* (via CT scans),[17] *elastic moduli* (via EMA mode frequencies—possibly substructure specific if the violin is dissembled), global *damping* (again via EMA results), and an accurate *shape* (reconstructed from a multislice CT scan).[17] These elements—combined—are the heart of the VIOCADEAS project. However, only time will tell whether they will provide the essential key to understanding a violin's quality through quantitative characterizations.

ACKNOWLEDGMENTS

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