Empirical Tools in Contemporary Violin Making: Part I. Analysis of Design, Materials, Varnish, and Normal Modes

Martin Schleske
Workshop for Violin Making
Seitzstr.4
D-80538 Munich, Germany

ABSTRACT

The perfection of the violin by the famed old masters is attributed to a long history of passionate innovative empirical work that has been replaced in modern times by a devotion to traditional prototypes. Improvements in violin design and performance during the 17th and 18th Centuries can be correlated with the development of progressively more demanding playing styles by composers, including Monteverdi, Corelli, and Torelli. The successful empirical approach of the old masters can be applied today using careful measurements, recordings, and documentation that allow us to relate specific changes in design to specific change in sound.

Our work has documented the major aspects of instrument design (arching, thickness graduation pattern, and body outline shape) and modal characteristics of about 90 fine reference instruments, including many old Italians. We have also measured the materials in old Italian instruments, which generally are similar to modern materials. For example, the density of an entire top plate from a Stradivari cello is 0.39 g/cm^3, which is not unusual. Further, our measurements indicate that the damping properties and modal characteristics of old and contemporary fine instruments are of comparable magnitude.

Tools available to the violin maker include selection of design, materials, varnish treatments, sound analysis, and modal analysis. Successive varnish layers can enhance or denigrate material quality. Making “tonal copies” using modal analysis at many steps of the working process allows the maker to change the geometry of the copy to compensate for material differences between the reference instrument and the copy.

INTRODUCTION

I first realized that the violin has a lot to do with experimental physics during my training as a violin maker at the Mittenwald school in the 1980s. Not only the physical fundamentals (being taught by Helmut A. Müller) but alsoNumerous articles on the subject published in Catgut Newsletters and Journals were of particular importance to me. At that time my impression was that many researchers tried to answer questions that no one had raised before. On the other hand, they had few answers to the practical questions raised by many violin makers. However, Erik Jansson’s studies always had a definitive connection to the real matters in violin making. This characteristic of his work has been maintained to the present [1]. I am honored to contribute to this issue in celebration of his 60th birthday.

> ***“. . . the essence of the old approach was continuous development, a history of passionate empirical work.”***

The following article is meant as a short introduction to some “empirical tools” that I use in my violin shop. I use modal analysis and sound analysis programs almost daily in my work as a violin maker, as a complement to the usual tools: knives, planes, chisels, saws, and so on. The new tools are used for support in tonal adjustments of fine instruments as well as in the making of new concert instruments. Over the years I have collected an extensive database on design and acoustical properties, based on studies of fine old instruments as well as evaluations during the making of new instruments. In this paper, the use of “empirical tools” in violin making is illustrated by examples that give the flavor of a tour through my violin shop and laboratory. This paper, Part I, gives an introduction to design, materials, varnish, and modes. Part II will cover psychoacoustical analysis, acoustical tools, and tonal copies.

TRADITION AND INNOVATION

How was it possible for the masters of the Italian violin making tradition of the 17th and 18th centuries to produce such perfect instruments? The culmination of the classical era of violin making was the result of a living tradition, accumulated over generations. Improvements in sound were kept while poor innovations were discarded. One generation carried their experiences over to the next—long, long history of trial and error. So it was that "centuries of empirical research led to the maturity of the violin." In order to continue the spirit of the classical violin making tradition, "tradition" must be broken. This is because the essence of the old approach was continuous development, a history of passionate empirical work.

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Probably there was a "major triad" of three interacting components - composition, musical interpretation, and innovative instrument making - that lay behind the development and perfection of such impressive "resonance sculptures" as the master works of the 18th century. Today we talk about "tradition in violin making" in contrast to "innovation". Nothing could be further from the history of violin making. This history bears witness to passionate creative power, as illustrated in the following examples:

- Claudio Monteverdi first called for 4th position violin playing (E_6, an octave above the open E-string; Marienvesper, 1610). This piece demanded greater virtuosity than was required in the works of other contemporary composers. His hometown was Cremona, Italy, the famous violin-making town of the Amati dynasty. It can be assumed that Monteverdi's demands on playing technique were soon transferred to violin makers and stimulated them to develop an instrument with greater playing capabilities.
- Arcangelo Corelli created his 12 Sonatas for Violin (Sonata a violine e violone o cimbalo; Rome, 1700), which formed part of the basic repertoire of violin players as recently as the 19th century. Even more important was the year 1680, when he composed the first "concerto grosso." Now the violin was lifted above the orchestra and became a solo instrument. For Antonio Stradivari this must have been a musical revolution. At that time he abandoned the model and arching style of his master, Nicolo Amati, and developed his own "long pattern." This development was his response to the demands of the new music style.
- It is easy to imagine how the creative power of Stradivari was stimulated when Torelli, in 1698, laid the foundations of the virtuoso violin concerto. Stradivari reacted to this innovation with another new model. It can be imagined that his so-called "golden period", starting about 1700, was influenced by this soloistic revolution. Hence, the climax of Italian violin making was in large measure a consequence of musical evolution. The first virtuoso composers and performers helped bring the violin to musical maturity.
- In a similar way, the development of the modern violin bow through François Xavier Tourte, Paris (1747-1835) was accelerated by the new violin schools led by Leopold Mozart and Josef Haydn. As new concert styles required new instrument designs, resulting in improved violins, now the enhanced playing technique called for new, improved bows.

Modern empirical methods can be used to pick up the "innovation" trail. Acoustical analyses of characteristics of the sound of violins by Antonio Stradivari, Guarneri del Gesú, and others make it possible to establish a direct connection with these masters. In this way they become contemporary teachers rather than simply historical prototypes. Scientific methods in violin making include careful documentation of all stages during the making of an instrument, including changes in design and wood treatment. Such a detailed "notebook" of the making process is necessary when comparing the sound of finished instruments. Only in this way can specific changes in design be related to specific acoustical features.

RECORDINGS OF SOUND

No scientific method can replace the trained ear, ultimate arbiter in violin making. Tonal adjustment, an important part of violin making, can be made more reliable using before and after recordings. A systematically organized archive of such recordings comprises an auditory "sound school", illustrating the effects of possible adjustments. Over the years we have compiled an extensive database of sounds based on tests of an assortment of instruments, and tonal adjustments in our shop (see Appendix A). Before the adjustment of a fine instrument, we ask the musician to do the following:

1. "Play something so I can hear why you have come here" (i.e. "What is the problem with the sound or playing properties?")
2. "Play something so I can hear why you play this particular instrument" (i.e. "What are your preferences in sound, playing technique, and interpretation?")
3. "Play open strings and scales" (i.e., "How even or uneven are timbre, volume, and response of the instrument?")

Answers to these questions help us to understand the kind of sound the musician is looking for. Furthermore, this procedure allows us to watch the interaction between musician and instrument. The choice of musical passages, and in particular how they are interpreted, helps us to answer the following fundamental questions: What characteristics of the instrument must definitely be retained in the tonal adjustment? What kind of "resistance," which sound, and which register is the musician looking for?

It must be emphasized that a fine professional musician is a highly reproducible measurement system. The best method for determining the quality of violins is probably one in which the musical relevance and reproducibility is highest. It goes without saying that "the musical relevance" of a violin played by a musician cannot be surpassed. However, the precision and reproducibility that a fine professional may demonstrate in playing, for example by repeating a passage many times in exactly the same way, is probably little known among scientists (who often have limited contact with professional musicians).

Example 1. An interesting experiment was made in our shop one day when two Stradivarius violins were at hand for tonal adjustments and associated recordings. The same passages were played and recorded, alternating between the two instruments. Without the musician's knowledge, some of the recordings (Mozart's Violin Concerto in D-major, 1st movement) were later edited to reproduce violin 1 on the left channel, simultaneously with violin 2 on the right channel. The match of tempo, phrasing, articulation and intonation is so close that for a long time a listener has the impression of hearing a single violin [Note: this recording is available for listening at www.schleske.de].

ANALYSIS OF DESIGN

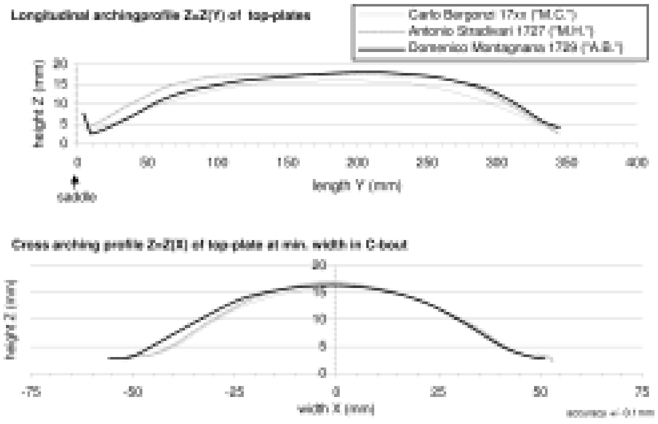
As stated above, the central empirical task for the violin maker is to relate the sound of the instrument to its design. In particular, the violin maker must learn to identify and judge the musical result of each change in the design. The major aspects in the analysis of the design are the arching, thickness graduation pattern, and the body outline shape.

Arching

In our shop, the determination of an instrument's arching is made by measurements of six cross-sectional profiles of the plates (maximum width of lower bout, lower corners, bridge position, minimum width of C-bouts, upper corners, and maximum width of upper bouts). In addition, longitudinal profiles are measured. All profiles are obtained by digital distance measurements using an X-Y coordinate table (Fig. 1). The advantages of this method are: (a) The true shapes of profiles are measured and reproduced with high accuracy; (b) The profiles can be reproduced with distorted proportions, for example making the body short and fat by reducing the length coordinates more than the height coordinates. In this way characteristic features of an instrument's shape (including deformation) can be emphasized; (c) Comparisons between instruments can easily be made by plotting two or more profiles on the same diagram.

Figure 1. Device for measuring arching profiles on an X-Y coordinate table.

Figure 2. Longitudinal- and cross-arching profiles of top plates of fine Italian violins by Carlo Bergonzi (17xx; date uncertain), Antonio Stradivari (1727), and Domenico Montagnana (1729). Measurement done using X-Y coordinate table and transducer (See Fig. 1). Accuracy: +/- 0.1mm.



Example 2. Cross and longitudinal profiles of three fine old Italian violins (Antonio Stradivari 1727, Domenico Montagnana 1729, and Carlo Bergonzi, 18th Century, date uncertain) are shown in Figure 2. The profile for the Stradivari is similar to that of his student Bergonzi, especially in the region near the plate edges, whereas the Montagnana has a fuller character. The longitudinal arching of Stradivari has clearly been deformed ("pressed out") due to the unusual thinness of the top plate. A depression in the top plate in the bridge region can also be seen. Note that the calibration of the zero line for each profile is based on the level of the slightly irregular glue-filled surface of the ribs at the corresponding measuring positions. This is why the maximum arch heights in the cross and longitudinal profiles may differ somewhat.

Thickness Distribution

Measurements of thickness graduation patterns are made using an electronic device developed in our shop. Thicknesses are measured

Figure 3. Device (prototype) for measuring the thickness graduation. The thicknesses are shown on the analog scale and processed by a computer to calculate the interpolation maps (*Instrument*: Cello by Domenico Montagnana, 1740).

by a magnetic sensor positioned on top of the plate of the assembled instrument (Fig. 3). The values are monitored on an analog instrument as well as being fed into a computer. In addition, the device is equipped with a voltage-controlled signal generator that produces a pitch which is directly proportional to plate thickness. A difference of 1/10 mm is converted to a change in pitch of one semi-tone. Using this equipment it is easy to get an overview of the thickness pattern and to track contours of constant thickness (i.e. follow paths giving the same pitch).

As has also been advocated by Jeff Loen [2], we prefer to use interpolation methods to transform the point-wise thickness measurements into a map showing regions of equal thickness by a color or gray code. This gives an immediate visual impression of the thickness pattern.

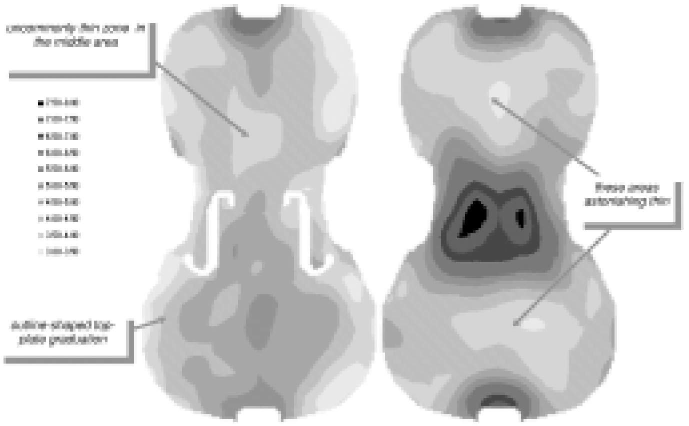
Example 3. Generally, the "art" of empirical research work lies in the ability to distill useful information from a large amount of data. An example of the gain in information obtained through thickness maps is shown in Fig. 4. Here the thickness distributions of six violins by Guarneri del Gesú are displayed in gray-scale shading. The data have been compiled from the extraordinary book on Guarneri del Gesú by Biddulph [3], and entered into our computer system. It is clear that the "Kreisler 1730" follows a different system than the other five instruments. The top plate becomes thinner towards the middle, while the back plate is generally thicker with a rather uniform distribution. The back plates of the other instruments show a more conventional "concentric" pattern, increasing in thickness towards the center. A striking similarity in the thickness distributions of the top plates can be observed for the "Stretton 1729" and the "Violon du Diable 1734".

Figure 4. Thickness graduations (in mm) of six violins made by Guarneri del Gesú. Plates are viewed from the outside. Diagrams were created using our interpolation program. Data from Biddulph [3].

The measured thicknesses can also be used for a statistical analysis, including averaging across several instruments, which makes it possible to display general differences. Finally, the thickness maps are used for evaluation of successive steps in the making and to illustrate different working concepts of old masters.

Example 4. The thickness distributions of a "composite" cello partly by Stradivari (top plate), partly by J.F. Lott (back plate) are

Figure 5. Thickness graduation of a cello: Top plate made by Stradivari, back plate by J.F. Lott.



shown in Fig. 5. This fine instrument, which possesses outstanding sound, was brought to our shop for tonal adjustment, including modifications of bass bar, fingerboard, soundpost, and bridge. The thickness distribution of the top plate largely follows the body contour, while that of the back plate is concentric.

Body Outline

The body outline is also measured by electronic determination of coordinates on the X-Y table. Once again, it is useful to plot several instruments on the same diagram in order to make direct comparisons.

Example 5. The outlines of back plates of two violins, Antonio Stradivari (1712) and Domenico Montagnana (1729), are shown in Fig. 6 (see also Appendix B).

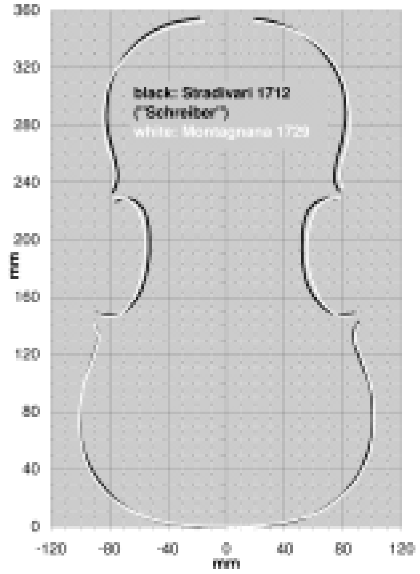
ANALYSIS OF THE MATERIAL

An established violin making practice, which is often applied when trying to make a fine instrument, is to rely on "tradition". This means that the work is guided by examining an existing, fine "reference" violin with desired timbral properties. An examination of the reference limited to the geometrical properties will, however, never lead to the goal, since it is the geometry in combination with material properties that determine the vibrational characteristics (normal modes), and hence the sound of the instrument.

The most relevant material properties for violin making are:

1. Sound velocity in the longitudinal direction of the grain
2. Sound velocity in the cross-grain direction
3. Density
4. Internal damping
5. Orientation of mechanical elements of wood (grain and rays)

Figure 6. Outlines of two reference violins: the "Schreiber" Stradivari of 1712 (black) and Domenico Montagnana, 1729 (white). Measured using X-Y coordinate table.



The importance of the last point follows from the fact that wood shows a strong anisotropy with regard to sound velocity and internal damping [4]. The orientation of grain and rays relative to the arching determines what fraction of the maximum available sound velocity will be attained in the two directions of the arching (longitudinal and cross). In fact, the influence of the local orientation of grain and rays across the plates is sometimes larger than the influence obtained by varying the distribution of plate thickness.

Of course, no two pieces of wood are identical. Also, detailed knowledge of the wood treatment of the reference instrument, including primer and varnish, is never available. The treatment of the wood particularly influences damping. The more the material properties of the reference instrument deviate from those of the instrument under construction, the larger the deviations from the geometry of the reference instrument that must be made in order to retain similar vibrational properties, and hence a similar sound. So, what strategy should be followed?

- The geometry of the reference instrument must be known as well as possible, because otherwise it will not be known *what to deviate from*. This is the reason for detailed analyses of the design of reference instruments (described above).

- A valuable preparatory task is to document the key acoustical parameters of the wood that will be used. By making a series of similar instruments from wood with varying material parameters and treatments it is possible to learn indirectly about the material properties of the reference instrument. The hypothesis put forward by Schelleng [5] and Meyer [6], that the acoustical quality of a piece of wood is determined mainly by the ratio between sound velocity and density, certainly seems to be correct according to our experience.

- It is desirable to obtain the best possible information about the material properties and wood treatment of the reference instrument. By using wood that is as similar as possible for the new instrument, the deviations from the reference geometry can be minimized. Among the many material parameters of the reference instrument, only the following can be determined:

  1. The sound velocity along the grain; and
  2. The sound velocity across the grain.
     (Note: these can only be determined indirectly as mean values by averaging over the normal modes)
  3. Density, including all treatments such as primer and varnish, can be measured in free plates (see Example 6).
  4. Damping can be measured by determining the bandwidths of the resonances in free plates.
  5. The orientation of the structural elements of the wood (grains and rays) can be determined, to some extent, by optical methods.

- Finally, the question must be raised whether wood with acoustically comparable material properties is available. In other words, are there any reasonable ways of deviating from the reference geometry with the pieces of wood at hand, in order to reach an acoustically comparable result? This question can only be answered indirectly and after the new instrument has been completed, using AB tests of recorded sounds from the two instruments. If the tests give a positive answer (no significant difference in sound) the answer is yes, it was possible. A psychoacoustical evaluation of the radiated sound is an important tool in all analysis and control.

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Some light will be shed on the strategic points mentioned above by describing experiences from our experimental work. It is often said that the old Italian master instruments exhibit material properties that cannot be duplicated today. This could relate to a "secret" treatment of the wood with particular mixtures of varnish, or to chemical or other long-term, slow processes that have modified wood properties.

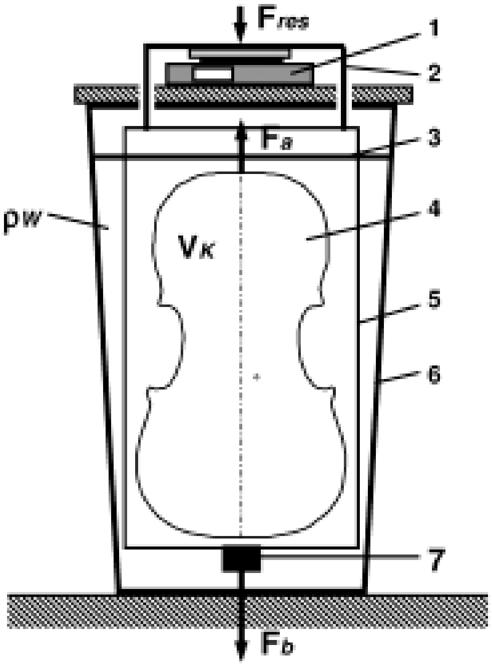


Figure 7. Device for measuring density δ [g/cm³] of a cello top-plate. Numbers are as follows: 1, scale; 2, metal handle; 3, water (known density δw); 4, top plate; 5, plastic sack; 6, barrel; 7, weight. Symbols are as follows: F_b, downward force of device without top; F_{res}, force with top plate inside bag; F_a, upward force of top plate, V_K, volume of the top plate.

Density

Example 6. What was the density of spruce used by Stradivari? Work in our shop gives some answers. The bass bar of the fine cello mentioned in Example 4 had to be replaced and this gave us an opportunity to determine the density of the Stradivari top plate without bass bar.

A very accurate method was used in which the weight of the top plate was determined when immersed in a liquid (water) of known density δ_W (Fig. 7). The top plate was put in a water-tight bag of synthetic material. A measurement rig was designed consisting of the plastic bag (5) with a weight (7) at its lower end, and a supporting frame (2) resting on an electronic balance (1) standing on top of a barrel (6). The weight was large enough to make the total force on the completely immersed top plate (in the bag) directed downwards, despite the buoyancy force F_a from the displaced water.

Equation I, gives F_b as the downward force on the measurement rig without the top plate, and F_{res} as the corresponding force with the top plate inside the bag. By this comparative measurement method, the error due to the plastic bag is cancelled out. F_b and F_{res} were determined from the readings m_b and m_{res} on the electronic balance.

$F_b = m_b g$ and $F_{res} = m_{res} g$ (Equation I)

where $g = 9.81\ \mathrm{m/s^2}$ is the acceleration of gravity.

Further,

$F_a = -G'$ (Equation II)

where G' is the so-called apparent weight of a fully immersed body.

Finally,

$\delta_K = \delta_W * G / (G\text{-}G')$ (Equation III)

where δ_K is the unknown density of the top plate, δ_W the known density of water, and G the "real" weight of the top plate as measured in air.

For this particular Stradivari top plate,

$$m_a = F_a/g = (F_b\text{-}F_{res})/g = (m_b - m_{res}) = (1480 - 870)\ \mathrm{gr} = 610\ gr$$

(Note: g denotes acceleration of gravity and gr the mass unit gram).

This gives $G' = -610$ gr according to Equation II. The weight in air was $m = 390$ gr, which gives $G = mg$. Finally, Substituting the known G and G' in Equation III gives the density of the varnished Stradivari plate as

$$\delta_K = 1.0 \cdot 390 / (390 - (-610)) = 0.39\ \mathrm{g/cm^3}.$$

The volume of this top plate (V_k) happens to be exactly 1000 $\mathrm{cm^3}$ ($V_k = m/\delta_K$).

A density of 0.39 $\mathrm{g/cm^3}$ is not unusual, but clearly in the lower range for spruce available today—even including wood from northern Italy. It must be emphasized that this value refers to the combination of wood, primer, and varnish, not to white, untreated wood. The densities of the primer and varnish are certainly higher than that of the wood itself. Further, these measurements say nothing about the original density at the time the instrument was made, which may have differed from the present. The measured density tells us only something about how this top plate compares to contemporary top plates.

Anatomy of Wood

Many rumors exist in the violin making world regarding historical methods for reducing the density of wood. A common hypothesis is that the membranes of the bordered pits in the tracheid cells were dissolved by attacks of microbes while the wood was immersed in a river or lagoon. The water could then penetrate the cells. Our studies, based on electron microscopy of wood obtained in repair work from violins by old Italian masters Joseph Guarneri filius Andreas, Domenico Montagnana, and F. Gagliano found no such

Figure 8. Scanning electron micrograph [7] of spruce top-plate of a F. Gagliano violin (anno 1780) showing pits in tracheid walls (2000 times magnification).

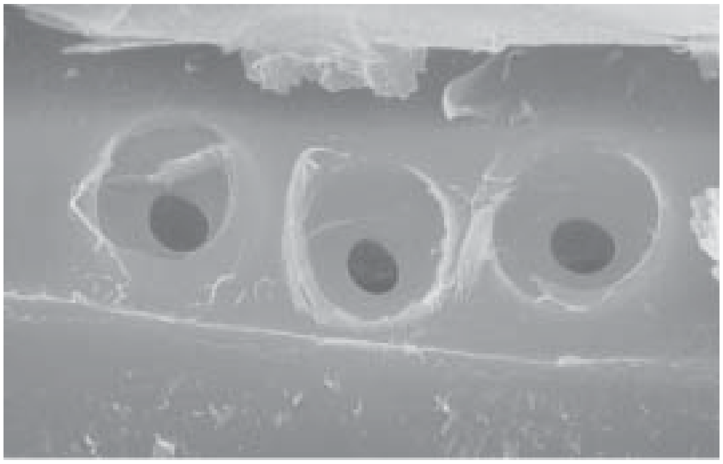
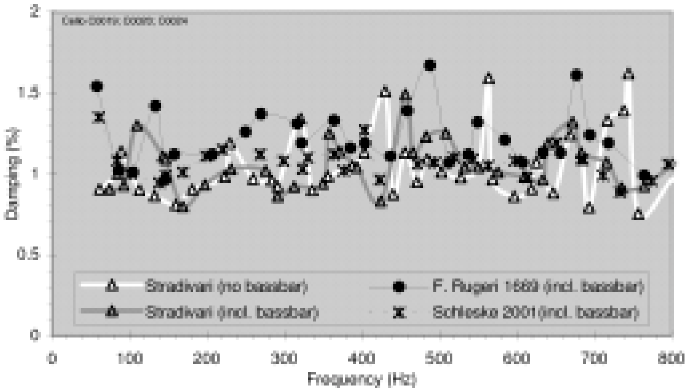


Table 1. Modal damping values averaged across all modes. "17xx" indicates that decade and year are uncertain.

Maker Name	Date	Bass Bar	Modal Damping (Percent)
A. Stradivari	17xx	without	1.04
A. Stradivari	17xx	with	1.06
F. Rugeri	1669	with	1.22
M. Schleske	2001	with	1.07

Figure 9. Damping of eigenmodes as a function of mode frequency (eigenfrequency) of cello top-plates by Stradivari 17xx (with and without bass bar), Rugeri 1669, and Schleske 2001. Note that the damping of spruce in the modern top plate is within the range of the old wood.



evidence. Similar microscope investigations of spruce fragments, conducted by Barlow and Woodhouse [21, 22] on a range of old instruments came to the same conclusion.

Example 7. Tracheid cell walls and bordered pits in a piece of wood from the top plate of a violin by F. Gagliano (ca. 1780); Fig. 8. The pits (diameter 0.012 mm) are clearly seen. They are not dissolved.

Damping of Resonances

An acoustically important material property is the internal friction, which, in combination with radiation losses, determines the 3 dB bandwidths of the resonance peaks. Does the internal friction of the normal modes of fine old instruments with desired sound differ from that of modern instruments? This question can be answered by comparing the 3 dB bandwidths of pairs of similar modes (which ought to have comparable radiation losses). Such differences have, if they exist, been assumed to be caused by some initial processing of the wood, a special composition of primer and varnish, or long-term aging processes. Comparisons of transfer functions used for modal analyses of assembled instruments as well as free plates give the following examples:

Example 8. Modal damping (half the 3 dB bandwidth normalized to the mode frequency) vs. normal mode frequencies was measured for two old cello top plates (A. Stradivari 17xx; F. Rugeri 1669) and a new instrument (M. Schleske 2001) (Table 1; Fig. 9). The plates were freely supported. In the frequency range analyzed here, no mysterious or anomalous damping values can be observed for these 300 year old cello top plates.

Table 2. Mean damping values obtained by averaging across all modes of some old and new instruments. Note: "x" indicates uncertain date. See Appendix C for a description of measurements.

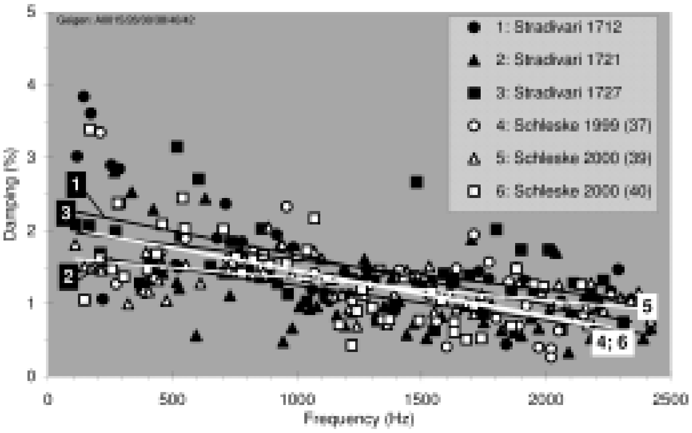
Maker Name	Date	Average Damping Value (Percent)
G. Grancino	1699	1.4
J. Guarneri (fil.Andrea)	1706	1.3
A. Stradivari	1712	1.5
A. Stradivari	1721	1.1
A. Stradivari	1727	1.5
C. Bergonzi	17xx	1.3
D. Montagnana	1729	1.3
J. Guarneri del Gesu	1733	1.2
J.B. Vuillaume	18xx	1.3
S. Zygmuntowicz	1996	1.2
M. Schleske	1999 (37)	1.2
M. Schleske	2000 (39)	1.3
M. Schleske	2000 (40)	1.4
M. Schleske	2000 (44)	1.2
M. Schleske	2000 (45)	1.4
M. Schleske	2001 (51)	1.3

Example 9. Analyses of finished instruments also reveal no major differences in damping between fine old instruments and contemporary instruments. A comparison of the damping values of three violins by Antonio Stradivari and three new violins built to his model (Table 2; Fig. 10), shows that the modal damping factors of the new instruments occupy the same range as those of the old instruments. The individual regression lines for the six instruments show the highest damping values for the Stradivari from 1712, and the lowest for the Stradivari from 1721. Regression lines (shown in white) for the new instruments are found in the range *between* these extremes. A decrease in the damping values towards higher frequencies, common to all instruments, is clearly seen. The decrease is about a factor 0.7 per decade. This decrease in damping with increasing frequency, which is reflected in sharper resonance peaks, is a highly desirable property. In combination with the increasing resonance density at higher frequencies this sharpening of the resonances contributes to the "modulability" (sound control by vibrato) of the instrument. In summary, our measurements indicate that the damping properties of old and contemporary instruments are of comparable magnitude.

THE "MUSICAL" VIOLIN VARNISH

In my opinion, the target of treating a violin with varnish is to achieve low damping in the finished instrument, ideally a reduction

Figure 10. Damping of eigenmodes of vibration in assembled violins: Three instruments by Antonio Stradivari are compared with three contemporary violins. Note that damping values are comparable. The regression lines of the new instruments (white) are between those of the "Schreiber" Stradivari (1712) and the "Hamma" Stradivari (1721).

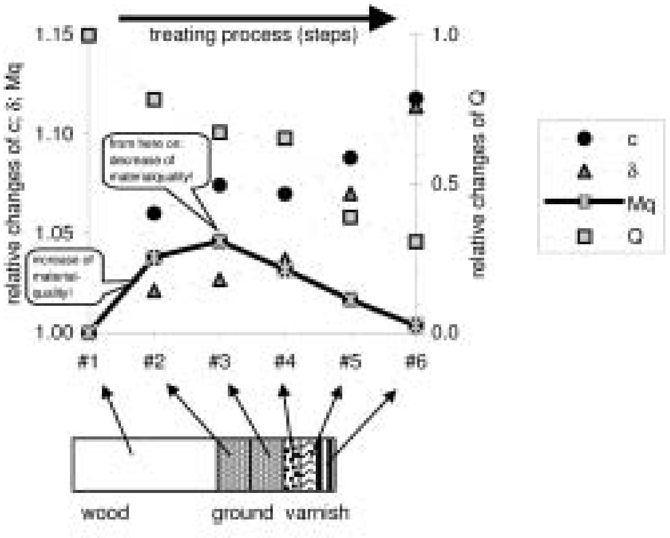


in damping compared to the untreated wood. A subsidiary goal is to achieve the highest possible increase in the ratio of sound velocity to density. A reduction of the damping corresponds spectrally to a reduction of bandwidths and an increase in heights of resonance peaks. As mentioned above this leads to a higher "modulability" of the sound [for a detailed explanation see Part II]. The second goal, an increase in the ratio between sound velocity and density, means an improvement of the "acoustical quality" of the material. A varnish with that second property will allow the instrument to be made with slightly reduced thicknesses and hence lower mass load. The decrease of mode frequency caused by reduced thicknessess will be compensated by the application of such a favorable varnish. The mode frequencies will be kept unchanged by the addition of the varnish. In this way the acoustical efficiency of the instrument is increased, as well as its dynamical range.

As the mode frequencies as well as the damping values may change significantly due to the treatment of the wood with primer and varnish [8, 9, 10], it is a good investment to learn about the influence of your own treatments. The whole concept of "varnishing" can include a number of treatments such as applying a filler and(or) ground layer, followed by many layers of varnish, and it is not only the final result which is of interest. The acoustics of the intermediate steps in the varnishing process are equally interesting. There is a danger that some single step in the process may have a detrimental influence on the final result, although it may happen that the loss is partly compensated or masked in a later step in the varnishing process.

Such undesirable intermediate steps cannot be detected in a single comparison between untreated and finished pieces. Each individual step in the treatment of the wood must be evaluated. Since (a) each treatment needs a certain drying time, and (b) the acoustical effects of the treatment change with time, it is necessary to conduct an evaluation of the varnishing process by making tests on a series of wooden samples (strips). The number of samples must be equal to the number of steps in the process, plus some untreated reference samples. The first sample receives only the first treatment, the second the first and the second treatment, and so on until the last sample, which undergoes all treatments in the varnishing process. The samples are allowed to dry for a substantial period of time, after which the differences in sound velocity *c*, density δ, and damping (quality factor *Q*) are determined and compared to the original reference samples. The resonance properties are measured using the standard method involving driving the free-free supported sample strip and observing the first bending mode [10]. The change in *material quality* $M_q = c/\delta$ due to the treatment is calculated for each sample. These changes compared to the original, untreated sample may be plotted vs. the successive steps in the varnishing process.

Figure 11. Step-by-step acoustical evaluation of the varnishing process. Note that the downward slope of the "material quality" (Mq) line reveals unfavorable steps in the varnishing process.



Example 10. Figure 11 shows successive steps in the treatment of spruce strips with thickness of 3.0 mm, and grain oriented perpendicular to the longitudinal direction. [Note: All values have been normalized relative to the untreated reference values because there is a possibility that the treated samples as well as the untreated reference samples were influenced by changes in climate during the treatment period. This way the effects of variations in humidity and temperature are compensated].

Figure 11 shows that the varnishing system analyzed here has only a limited positive influence. The two first treatments (ground) that increase the sound velocity by 7.4 % and the density by only 2.7 % give a noticeable increase (4.6%) in material quality. The following step #4 (treatment by a layer of rosin oil) gives, however, a relatively higher increase in density, and the material quality drops. In this step some of the positive influence of the grounding in steps #1 and #2 is lost. The same effect is found for the following treatments with a fat oil varnish. After the final treatment (step #6) the material quality is similar to that of the original wood. The sound velocity has increased by 11.8% and the density by 11.4 %. It would have been better if the initial trend could have been kept, with a faster increase in sound velocity than in density. In that case, it would have been possible to make the violin with slightly thinner plates in order to reduce the mass load, and thereby increase the acoustical efficiency. This way, the shift in mode frequencies and associated change in sound that follows with thinner plates would have been compensated in the varnishing process.

The varnishing system we use in our shop consistently gives an increase in mode frequencies of about 6 % compared to the untreated

Figure 12. Modal analysis of a violin showing impact hammer for measuring excitation force and accelerometer (at the upper bridge corner) for measuring response.

(white) instrument. In contrast to the disappointing example in Fig. 11, a varnishing process has been reported which *reduces* the damping compared to the untreated wood [10].

MODAL ANALYSIS

We will now turn to some important tools for acoustical analysis. Methods for visualization of modes like hologram interferometry [11] were used on violins by Jansson and others as early as 1970 [12]. Recently Bissinger started a comprehensive project in order to create a database on the design and acoustics of stringed instruments, including modal parameters [13]. Modal analysis was first applied to the violin in 1983 by Müller [14], and later by Marshall [15,16]. In 1989 it was used for the first time during the making of a violin [17]. Still, few violin makers use it as an aid in their work. That is surprising since modal analysis gives a very intuitive view of the modes of vibration, which is the primary function of the instrument.

With the use of modal analysis it is possible to make an acoustical "fingerprint" of a violin, showing the normal modes (often called "resonances"). The modes depend upon all the properties of the vibrating structure, including geometry as well as material. With other methods, these two sets of properties have to be studied independently. The particular combination of material properties, arching, thickness distribution, body shape etc. (in other words all of the parameters that can be varied in violin making), define certain distributions of specific stiffness and mass, which in turn determine the modes of the instrument. Modal analysis of mode shapes, mode frequencies, and damping factors shows how the parameters of the material and design combine into a single picture. At the same time, the modes are the basic components that determine the vibrations in the violin, and hence the sources of the radiated sound of the instrument. Viewed in this manner the modes are the obvious link between design, making and sound.

An Intuitive Method for Diagnosis

Modal analysis fosters an intuitive understanding of the function of the violin, as the modes can be displayed animated on the computer screen. The violinmaker can then watch how the violin's corpus bends, pumps, and twists. He does not only hear but suddenly begins to see what will happen to the instrument when the musician excites it. He thus learns to understand the function of the instrument, and begins to develop a deeper understanding of the resonances his making process produces. Even if the methods might look a little technical, computer analysis does not tell him what to do. It just shows him what happens. The art of violinmaking is to create a certain resonance sculpture. Usually he cannot see resonances, he can only hear what they are responsible for: the tone of the instrument. But modal analysis is a method that reveals what he has created: the resonance sculpture!

That is why my passion as a violinmaker is focused on resonances and why I find modal analysis and sound analysis to be exciting tools. They open a new sphere of intuition and experience as one begins to understand things that usually cannot be seen. Intuition and experience will guide all further decisions on what modifications of the developing corpus will bring its resonances closer to what you are aiming for (which may be to match the resonance profile of a fine reference instrument).

Table 3. B1 frequencies of 11 old violins (sorted by increasing B1 frequency). "x" indicates uncertain decade or year.

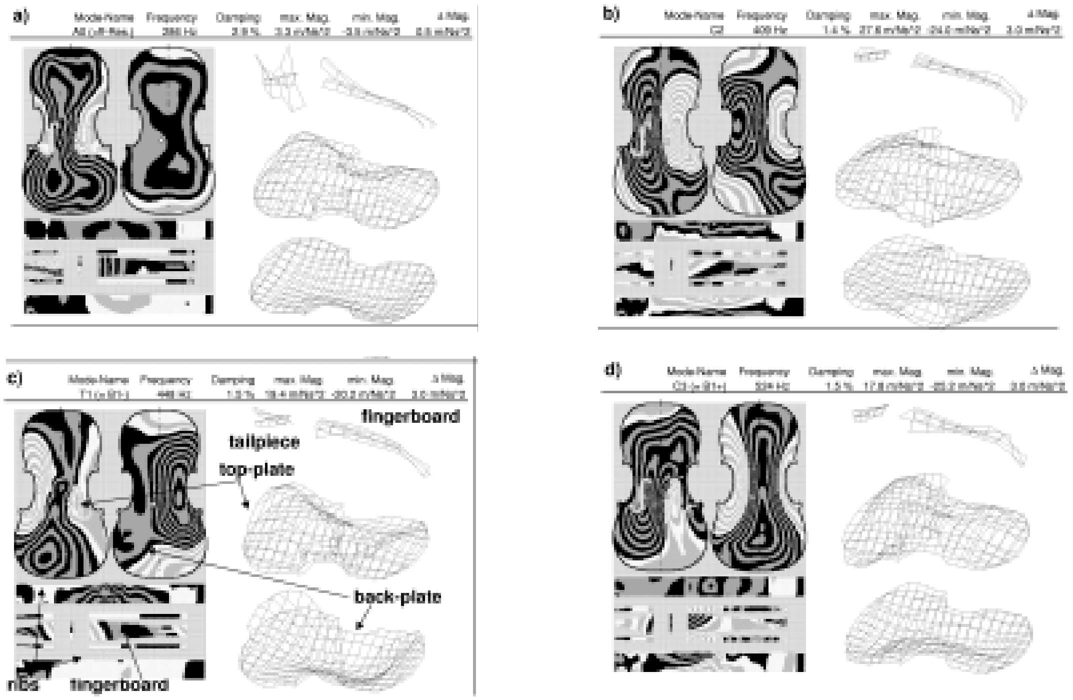
Maker Name (Location)	Date	B1 Mode Frequency (Hz)
Giambattista Rogeri (Brescia)	16xx	500
Jean Baptiste Vuillaume (Paris)	1872	506
Antonio Stradivari (Cremona)	1712	513/524*
Carlo Bergonzi (Cremona)	17xx	519
Domenico Montagnana (Venice)	1729	519
Antonio Stradivari (Cremona)	1721	517/527*
Giacomo Rivolta (Milan)	1837	524
Antonio Stradivari (Cremona)	1727	533
Giovanni Grancino (Milan)	1699	541
Joseph Guarneri del Gesú (Cremona)	1733	544
Joseph Guarneri fil Andreae (Cremona)	1706	565

* Split B1 mode due to torsional motion of the fingerboard [details see PartII].

Figure 13. The typical lowest eigenmodes of a Stradivarius (1712) violin. In contrast to the high variety of different plate modes, these four eigenmodes are in general observed on all violins. The mode frequencies and details in the mode shapes differ from instrument to instrument. They give valuable clues about the acoustical function of the instrument. Together they form the individual "acoustical fingerprint" of the violin.

Left-hand pictures (a through d): Contour diagrams of the mode-shapes. View from the outside. Gray-black areas vibrate in opposite phase with gray-white areas. Nodal lines (lines of no amplitude) between black and white ring. Read rings of vibrating zones like height-lines of mountains on a topographical map. Absolute Amplitude difference between two adjacent black (or two adjacent white) rings: see Δ Mag. (in m/Ns^2) above Fig. 13a...d.

Right-hand pictures: Frozen pictures of screen animation. Both maximum displacement and undeformed situation are plotted.



a) *A0 Helmholtz resonance*: 286 Hz. A mode with strong "breathing" of the whole corpus with very effective radiation of sound due to the air vibrating in the *f*-holes. Notice it by playing a chromatic scale on the G string. The region around C# will sound a lot more sonorous than the other notes. The reason: the fundamental of C# corresponds with the Helmholtz resonance. Note bending of the fingerboard.

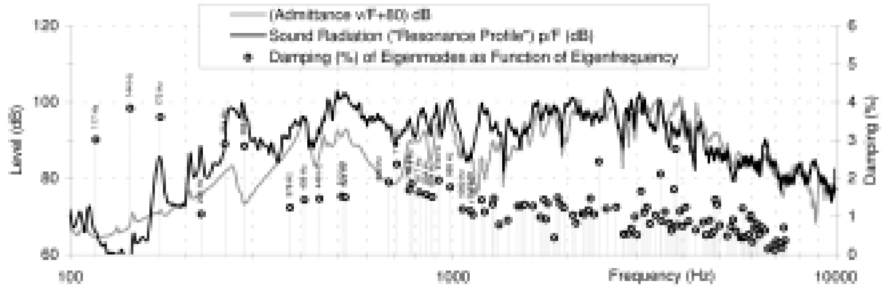
b) *C2 corpus mode*: 409 Hz. A strongly twisting, weakly radiating mode. It is the only mode with almost identical mode-shape patterns on top and back plates.

c) *T1 corpus mode*: 448 Hz. The lower of the two strong corpus modes. Strong radiation due to the pumping movement of the back plate and the strong vibration area in the lower flank of the left top plate side. Note the strong (in plate) vibrations near the ribs at the bass bar side: this is due to the strong maximum vibration of the back plate at the edges of the C-bout (bass bar side).

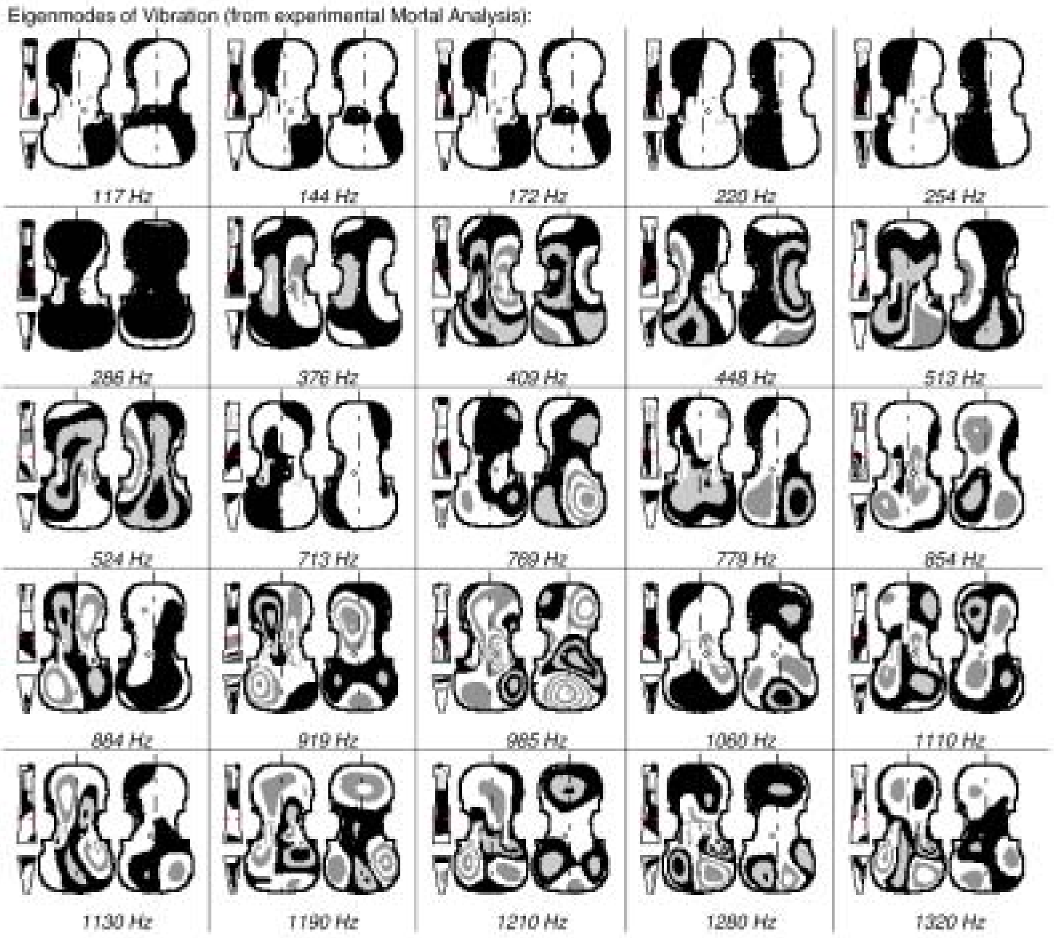
d) *B1 corpus-mode*: 524 Hz. Large vibration zone in phase on the top-plate due to the function of the bass bar. Back plate edges vibrate in opposite phase to center of back plate, performing strong bending in cross direction. Strongly radiating mode.

Figure 14. An extensive acoustical protocol of a Stradivari violin (1712). The frequency functions are:

a) Black curve: Energetic averaged "Resonance profile" of sound radiation p/F (p = sound pressure; F = excitation force). Gray curve: Energetic averaged mobility of both bridge feet (admittance v/F). Data points: Damping values as function of eigenfrequency (right vertical axis).



b) The first 25 eigenmodes of vibration of the Stradivarius. Measured by experimental modal analysis. Mode frequency (Eigenfrequency)values appear below each mode shape. White-gray areas vibrate in opposite phase with black-gray areas. See text for details.



Eavesdrop on Stradivari

Of the almost 90 instruments that we have examined by modal analysis in our shop during the last few years, a "shining star" is the "Schreiber" Stradivari of 1712 (Fig. 11), an outstanding example of violin making at its highest level (for details of the measurement method see Appendix C).

Example 11. The four most important low modes of this Stradivari are shown in Fig. 13. Modes with these shapes are observed in almost all violins. In contrast, the high-frequency plate modes starting at about 650 Hz are very different between instruments.

We regard the B1 mode as a kind of "leading mode" for the tonal color of the instrument; it acts as a "tonal barometer." A B1 frequency below 510 Hz is characteristic of a somewhat "soft" violin with dark sound, lacking "resistance." In contrast, a B1 frequency above 550 Hz is found in "stubborn" violins with bright sound, possibly with a tendency to harshness, and with strong "resistance" to the player. Hutchins has observed this effect and stressed the importance of the frequency difference between the B1 and A1 modes [18]. The frequency of the A1 mode - which is a "longitudinal" air mode with a single nodal line at half the body length [19, 20] - varies very little around a value just below 500 Hz due to the almost standardized length of the violin. The frequencies of the B1 mode are, however, widely scattered in different violins (Table 3).

A detailed illustration of the acoustical properties of the Stradivari violin from 1712 is shown in Fig. 14. The frequency responses show the "resonance profile" of the radiated sound (black curve), calculated as the RMS average of the normalized sound radiation (sound pressure divided by excitation force) at different angles in the room. The other frequency response (gray) is the quadratic average of two admittance measurements, in which the excitation force has been applied at the upper corner of the bridge (G-string side) in the bowing direction. The detection of the resulting motion was made at the two bridge feet.

It is clear that the admittance does not give a very good prediction of the radiated sound from the instrument, although it is better above about 1300 Hz. The reason is the increase in the ratio between the bending wavelength in the plate and the wavelength of the air-borne sound, which improves the sound radiation efficiency. The damping of the modes is plotted with data points at the corresponding mode frequencies. The lower part of Figure 14b shows the mode shapes of the first 25 modes (up to about 1320 Hz). The typical difference between body resonances and plate resonances is clearly seen, among other things. In the body resonances the top and back plates move as a single unit with strong coupling via the ribs. The nodal lines run across the ribs from one plate to the other, which means that the body bends and twists as a homogenous body. This property is seen for all modes up to B1 (524 Hz). The plate resonances, in contrast, are characterized by smaller "islands of vibration" separated from each other, more numerous the higher the frequency. The nodal lines run in many cases parallel to the contour of the body. In these modes the violin behaves like a membrane divided in many parts, vibrating in alternating phases. The typical characteristics of plate resonances start with the mode at 769 Hz. It has an efficient, asymmetric vibrational shape with an antinode in the lower right part of the bottom plate. It is easily identified as a peak in the resonance profile of the sound radiation, and provides a substantial part of the sound radiation. Body and plate resonances are always clearly separated by a border line at about 700 Hz in the frequency responses of the sound radiation as well as in the admittance. In the frequency range up to 2340 Hz, 48 modes of this particular Stradivarius violin were identified by modal analysis (see Appendix C for details about measurements).

A collection of complete illustrations for different instruments is very useful for making acoustical relationships between two instruments visible. When making "tonal copies" the use of modal analysis at many steps of the working process allows the maker to compensate for differences between the reference instrument and the copy caused by differences in the material, by making changes in the geometry. As the modal analysis shows the vibration shape of each single mode, it is possible to identify the "sensitive zones" for each mode. In these zones, a modification of the plates or other parts of the instrument gives maximal shift in the modal frequencies and damping. In this way, modal analysis can be used to support the "design of violin sound", when striving towards a specific goal.

(To be continued in the next issue of the CAS Journal. "Empirical tools in contemporary violin making: Part II. Psychoacoustical analysis and use of acoustical tools)

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NOTE ABOUT TERMINOLOGY

We use the terminology in Refs. [23-27], in spite of the fact that it is inconsistent and partly misleading.

- A0 (Hutchins) = Helmholtz resonance (H.A. Müller) = *ff*-hole resonance (Cremer)

- C2 (Jansson)
- T1 (Jansson) = B1–(Hutchins/Bissinger)
- B1 = B1+ (Hutchins) = C3 (Jansson) = main corpus resonance (H.A. Müller)

In my opinion it would be sufficient to denote three categories of resonances, using *A#* for air resonances, *C#* for corpus (body) resonances, and *P#* for plate resonances. These three categories are unambiguously defined, independently of the quality of the instrument. The historically motivated use of several other terms, like T1 for an often pronounced top plate mode, is strongly dependent on the characteristics of the individual instrument. In fine instruments with outstanding sound, the T1 mode ("1st strong top plate mode," Jansson) is not at all limited to the top plate. The motion of the T1 mode is often of equal amplitude in the top and back plates, sometimes even larger in the back plate.

APPENDIX A

Recordings of Sound

Microphone: Sound level meter B&K 2237. Distance from violin: 1 m vertically above the sitting player. Ceiling height: 3.5 m. Reverberation time of the room (violin shop): 0.6 s. Recording directly on hard disk. Software: digidesign. Near-field monitors: EMES. The judgment of the recordings by many players runs like this: "The recording is brutal. Everything is heard. But I have seldom recognized my own instrument so clearly."

APPENDIX B

About the Instruments

"Schreiber" Stradivarius, 1712

Made by Antonio Stradivari in Cremona, 1712. It belonged to Dr. Schreiber in St. Petersburg after whom the violin is named. Prior to 1900 it was played by H. Wieniawski. About 1900 it was sold to Oswald Möckel and Dr. Louis Ravené in Berlin and played by Huberman. In 1937 it was passed over to Hans Basserman who shortly afterwards emigrated to the U.S. The instrument was played by Pinchas Zukerman between 1968 and 1972 and is documented on many recordings, for example Concerto for Violin and Orchestra No: 5 a minor Op: 37 by Henri Vieuxtemps (CD Sony Classics SBK 48274). In 1976 it was on loan to Daniel Heifetz. Today the violin belongs to a CAS member and customer of our violin shop. It is played by one of the members of the SWR Sinfonieorchester Freiburg/Breisgau.

References: [28, 29], Certificates by J.A. Beare, London and A.F. Moglie, Washington D.C., and others.

Dominico Montagnana, 1729

This violin has an outstanding Venetian varnish, and a warm, voluminous sound. For a period of ten years it belonged to the concert master Kolja Blacher of the Berlin Philharmonie. Today it is played by Alban Beikircher, a young soloist.

Guarneri del Gesu, 1733

The instrument belongs to one of the concertmasters of the Münchner Philharmoniker. It is the present reference instrument for our work in the shop.

APPENDIX C

Measurement of Damping and Modal Analysis

Support of instrument: Foam rubber pillows (height 12 cm) at the upper and lower end blocks.

Measurements: Transfer functions $FRF(f) = a(f)/F(f)$; number of samples 4096. Bandwidth: 3.2 kHz. Software: difa d-TAC
Hardware: difa Measurement Systems FA-100 (4 ch FFT analyzer)

Number degrees of freedom (DOF): 595 in each mesh.

Excitation at all DOF's: Impact hammer PCB 86C80 with plastic tip (red).

Sensor: Accelerometer PCB 352B22 (0.5 g) (fixed horizontally at the top on the G string side of the bridge).

Analysis: STAR Structure Modal Analysis; Advanced Curve Fitting (Advanced options: tolerance F = 1.00 Hz; D = 1.0 Hz; Model size = 30; Bandwidth of curve fitted FRF is 512 lines; more than 3 separate curve fits in the observed frequency range).

Mode shapes: Scaling of mode shape amplitudes: Residues (absolute values). All residues were divided by $2\pi f$ (mobility representation) in order to allow a comparison of the modes in a data set.

Visualization of the modes by interpolation of the residues (58,704 points) and computation of iso-amplitude contours.